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Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel. Volume 2. Heavy-Duty Vehicles

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In July 1989 the President submitted to Congress his Administration's proposals for revising the Clean Air Act. One major component of his plan is the Clean Alternative Fuels Program. This program would replace a portion of the motor vehicle fleet in certain cities with new vehicles that meet stringent air emission limits operating on clean burning fuels such as methanol, ethanol, compressed natural gas, liquified petroleum gas, electricity, and reformulate gasoline.

This report, released by EPA, is the third in a series of reports that will discuss the economic and environmental issues associated with each of these fuels.

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Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel

Volume II

Heavy-Duty Vehicles

April 1990

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This report addresses the economic and environmental issues associated with the use of compressed natural gas as a motor vehicle fuel. Volume I analyzes the use of compressed natural gas as a fuel for passenger cars and light trucks. Volume II considers the use of compressed natural gas as a heavy-duty vehicle fuel.

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CHAPTER 1

INTRODUCTION

This report is one in a series of reports which EPA is preparing in order to describe the environmental and economic impacts of various clean alternative fuels. It deals with the use of compressed natural gas (CNG) as a fuel for heavy-duty vehicles. CNG, of course, also is used in light-duty vehicles. However, the nature and issues associated with these two areas are sufficiently different that EPA has chosen to issue separate volumes on light-duty and heavy-duty uses of CNG. Other reports in this series already issued or being prepared deal with methanol, ethanol, liquified petroleum gas, electricity and reformulated gasoline. In sum, they will provide a comprehensive review of the choices of clean alternative fuels which might be used to move America toward cleaner cars and trucks and reduced dependence upon petroleum.

This report was provided in draft form for review and comment to other EPA offices as well as a variety of external organizations. A number of comments were received in response to this request for review. To the extent possible these comments have been incorporated into this final version of the report

When considered as a vehicle fuel, CNG is distinctly different from conventional gasoline or diesel fuels in that it is a gas at all normal temperatures and pressures. Thus, it requires different approaches to vehicle refueling and to fuel storage on the vehicle. On the other hand, being gaseous means that the entire CNG fuel system must be a closed one, eliminating evaporative emissions entirely. Because of this, and other clean burning characteristics of CNG, it offers the potential for significant emission reductions in vehicle uses.

Considerable experience with CNG use in a variety of heavy-duty applications already exists. CNG has been successfully used to power vehicles ranging from light delivery trucks to full-sized urban buses. These applications have generally been based upon conversions of existing truck engines to run on both gasoline and CNG; which has allowed the use of CNG fuel even though it is not widely available at fueling stations. However, when considered from the perspective of use as a clean alternative fuel, the use of dedicated vehicles, which can run only on CNG, assumes a dominant role. Such vehicles, because they can be optimized to make use of the specific combustion properties of CNG, hold promise of much greater emission reductions and fuel consumption gains than do dual-fueled vehicles.

The remainder of this report examines in greater detail the use of CNG in heavy-duty vehicles, both current and future. It begins with an introductory overview of current and historical applications for CNG vehicles, and the identification of types of uses where the most ready growth of CNG would be possible. Chapter 3 describes CNG engine technology and presents emissions data for CNG fueled heavy-duty engines. Based upon projections of potential progress in emissions control and fuel consumption, emissions estimates for more advanced future CNG engines are also developed. Chapter 4 reviews the costs associated with CNG use. These include vehicle costs for engine and fuel tank hardware, fueling station costs and fuel costs. Since heavy duty applications for CNG represent a relatively small impact on overall natural gas use, fuel cost estimates are based upon the assumption that current natural gas supplies to the domestic market can be used, with negligible impact on gas prices. Finally, Chapter 5 provides a comparative analysis of the environmental benefits of CNG compared to both gasoline-fueled and diesel engines. This analysis focuses principally on the areas of ozone, air toxics and global warming and shows that CNG indeed has the potential to provide significant emissions benefits.

As in the other reports in this series, this report deals with the topics of CNG technology and the economic and environmental impacts of heavy-duty CNG use. There are other matters related to the introduction of alternative fuels which are not specifically addressed. These include such things as establishing emissions standards and test procedures, overcoming institutional barriers, etc. While such questions are important, they are outside the scope of these reports.

CHAPTER 2

USES OF CNG IN HEAVY-DUTY VEHICLES

The purpose of this chapter is to provide background information on the use of compressed natural gas (CNG) in heavy-duty vehicles in the United States, and to discuss generally the potential for future growth in this area. The Chapter will address economic, technological, and regulatory factors only peripherally as needed to explain certain projections and conclusions; later chapters in this report will detail findings in these areas.

This chapter is organized into three sections. Section I addresses the historical use of CNG in heavy-duty vehicles, Section II describes recent activities in the conversion of heavy-duty vehicles to CNG, and Section III describes the potential future market for CNG in heavy-duty vehicle applications.

I. Historical Use of CNG in Heavy-Duty Vehicles

Experience with and interest in CNG as an alternative motor-vehicle fuel differs significantly around the globe. Use of CNG in heavy-duty vehicles throughout the mid-1970s in the United States was sporadic and isolated at best, while use of CNG in parts of Europe, South America, and Asia has been more enthusiastic. While economics was the primary motivating factor for CNG use both abroad and in the United States, environmental and political concerns have also played an important role in the United States.

CNG as a vehicular fuel has been popular in other parts of the world since the mid-1930s. In Italy, for example, use of CNG as an alternative fuel began in 1935 as part of the National Economic Policy, which called for self-sufficiency in all materials. Gasoline shortages during World War II increased the demand for CNG, which was used for both public transportation and private vehicles. At its peak from 1945 to 1960, CNG captured about ten percent of the Italian vehicle fuel market.[1] When gasoline became less expensive and more readily available in the 1960s, however, CNG's share of the fuel market fell. The international appeal of CNG continues to be strong: New Zealand has 125,000 cars and trucks converted to natural gas; Canada has 20,000 natural gas vehicles; Argentina has 15,000 natural gas vehicles; and the Soviet Union has 200,000 vehicles, with plans to convert another 300,000 by the end of 1990.[2]

Use of CNG in heavy-duty vehicles in the United States was given a boost in the 1970s with the general increase in concern for the environment. Auto emissions were identified as a major source of air pollution, spurring some interest in development of alternative fuels. During this period, several companies offered systems to convert vehicles from traditional fuel use to natural gas. The market was not well defined or financed, however, and the demand for vehicles fueled by natural gas remained low. An estimated 15,000 CNG-fueled vehicles were operating at this point in time in the United States, a fraction of which were heavy-duty vehicles.

The "energy crises" of the 1970s generated a concern for energy and oil security in the United States, and temporarily increased interest in alternative fuels. The United States made a concerted effort to find substitutes for foreign oil in order to weaken the hold of the OPEC cartel on world oil prices. The transportation sector appeared to be the key to meaningful reductions in oil consumption. Interest in alternative fuels waned, however, as significant investments in energy efficient technologies between the mid-1970s and mid-1980s, combined with an increase in the world's oil supply, eventually forced lower oil prices.

Motivated by the potential for substitution of CNG for gasoline and diesel fuel to reduce fuel costs, improve declining urban air quality, and create energy security, a variety of interrelated market and regulatory forces caused renewed interest in CNG use in heavy-duty vehicles during the 1980s. This renewed interest stimulated CNG-related development, resulting in a viable CNG heavy-duty vehicle market. This market currently includes an estimated 1,500 CNG heavy-duty vehicles* served (along with light-duty vehicles and trucks) by up to 300 refueling stations (mostly owned by gas utilities), and supported by several utilities, approximately 80 CNG vendors, and related gas interest associations.

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* For purposes of this report, "heavy-duty" vehicles are defined to have a gross vehicle weight (GVW) of more than 8,500 pounds. There is, however, a disparity between this definition and the definition used by the Department of Transportation (DOT). Dot defines a "heavy" truck as: 1) a single-unit truck with GVW greater than 26,000 pounds, 2) a tractor-trailer combination, 3) a truck with cargo trailers, and 4) truck-tractor pulling no trailer. Some trucking associations use alternative definitions, such as a GVW in excess of 20,000 pounds. Differences in definitions may make comparisons of vehicle statistics difficult.

II. Recent Progress in CNG Heavy-Duty Vehicle Applications

As shown in Figure 2-1, the number of heavy-duty vehicles in the United States, which represents the maximum potential market for CNG-fueled heavy-duty vehicles, is quite large. Efforts by the CNG industry to penetrate this heavy-duty vehicle market have met with mixed success. Figure 2-2 shows the CNG heavy-duty vehicles that exist today in the United States by application, including dump trucks and heavy-duty pickup trucks, school buses, transit buses, United Parcel Service (UPS) delivery trucks, and trash collection trucks. Of the estimated 1,500 heavy-duty vehicles that have been converted to CNG, about 43 percent are heavy-duty dump trucks and pickup trucks, and 18 percent are school buses. Unidentified vehicles in the Figure represent that fraction of the total number of CNG heavy-duty vehicles that the American Gas Association estimates exists but which have not been identified to date in their surveys. That number should be considered only an approximate value.

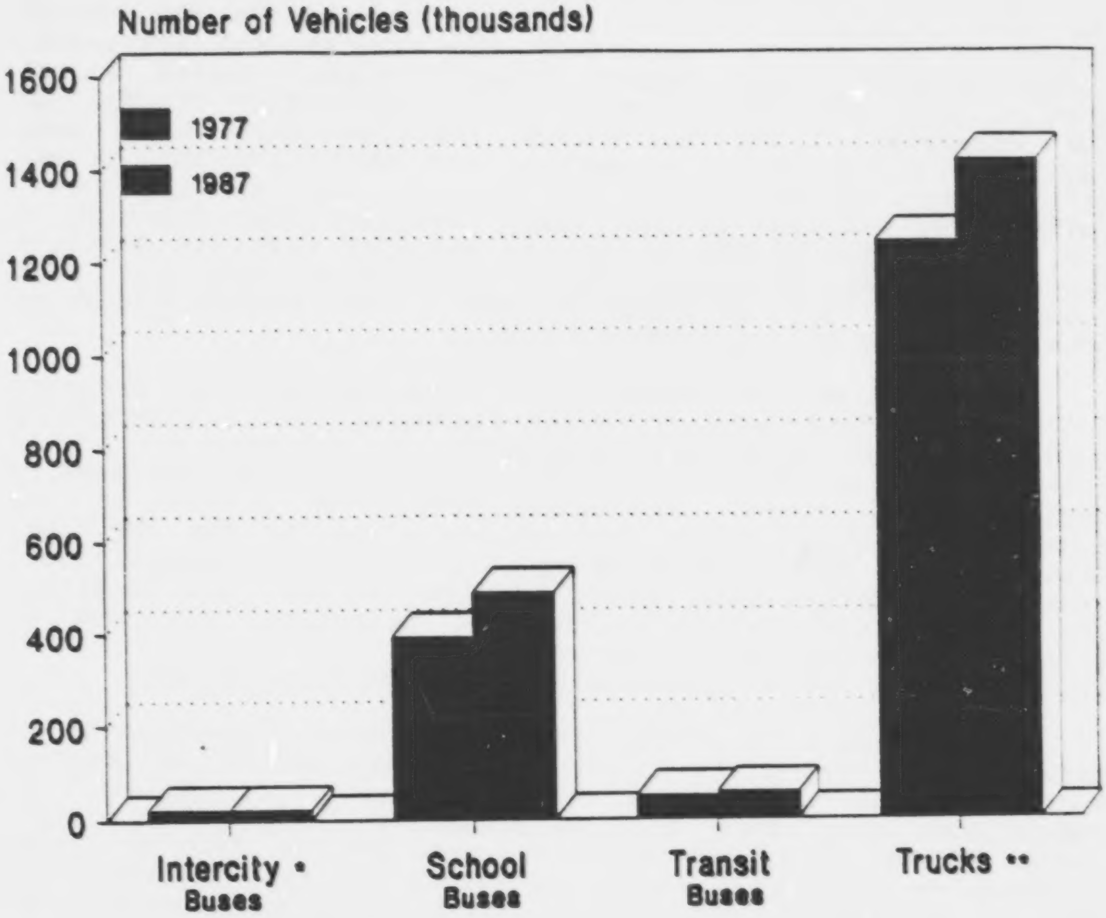
As detailed in Table 2-1, the conversion programs completed to date were primarily sponsored (and predominantly funded) by gas utilities, frequently in conjunction with a transit authority or school district, and have been designed to test evolving diesel conversion technology. Most of the conversion projects have involved only one or two vehicles. There are a few notable exceptions to these generalities, including a cooperative effort between two Ohio gas companies and Flxible Corporation to develop prototypes for use in transit districts, and a Garland, Texas school district that decided on its own to dedicate its fleet of buses to CNG.

Texas itself is worthy of further note. This state is attempting to bring its four non-attainment areas (Dallas-Fort Worth, Houston-Galveston-Brazoria, Beaumont-Port Arthur, El Paso) into compliance through proactive legislative action. Texas Senate Bill 769 requires the use of CNG or other alternative fuels that reduce emissions in rapid transit buses and, if necessary, certain local government and private fleet vehicles in non-attainment areas for either ozone, carbon monoxide (CO), oxides of nitrogen, or particulates. By 1994, 940 transit buses are to be converted to CNG with the possibility of 4,038 school buses to be added to that figure (122 of which are presently CNG fueled). Details on Texas' legislative implementation schedule are given in Figure 2-3.[4]

The use of both prototypes and entire fleet conversions over the last decade has had the effect of chronicling the evolving technology of CNG-conversion vehicles, beginning with

FIGURE 2-1

U.S. Heavy-Duty Vehicle Market



1977 & 1987 Heavy-Duty Vehicles by Application

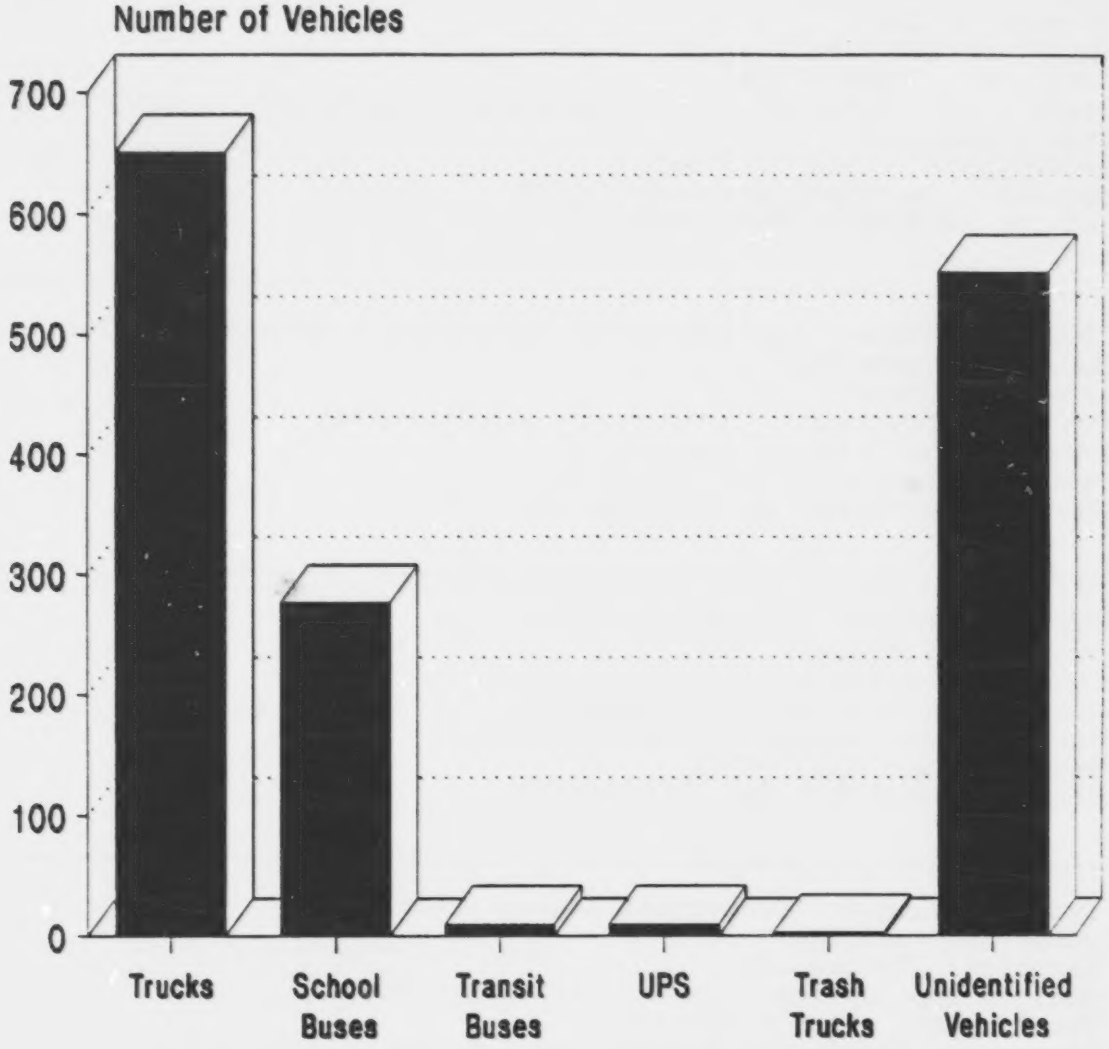
* Defined to include Class I, II, III interstate carriers, all of which report to the Interstate Commerce Commission.

** Figures for trucks are estimated. DOT designation of single unit trucks is based on the carrying load, not the gross vehicle weight.

Source: U.S. DOT/RSPA, NATIONAL TRANSPORTATION STATISTICS, Annual Report, 1989. Cambridge, MA.

FIGURE 2-2

Distribution of Existing CNG Heavy-Duty Vehicles



CNG Heavy-Duty Vehicle Applications

Sources: American Gas Association, the Natural Gas Vehicle Coalition, Representatives of Gas Utilities and Representatives of Vehicle Conversion Suppliers.

TABLE 2-1

Existing CNG Heavy-Duty Vehicle Applications

Type of vehicle: Bi-fuel four-stroke diesel bus (80% diesel/20% CNG)
Number of vehicles: 1
Location: Phoenix, AZ
Goals of application: Emissions reductions, technology demonstration
Participant: City of Phoenix
Sponsor: Southwest Gas Corporation
Source: Southwest Gas Corporation

Type of vehicle: CNG-dedicated two-stroke diesel transit bus
Number of vehicles: 1
Location: Tucson, AZ
Goal of application: Technology demonstration
Participant: City of Tucson
Sponsor: Southwest Gas Corporation
Source: Southwest Gas Corporation

Type of vehicle: Heavy-duty truck
Number of vehicles: 630
Location: Arizona
Goal of application: Economics
Participant: Southwest Gas Corporation
Sponsor: Not Applicable
Source: Southwest Gas Corporation

Type of vehicle: Two-stroke diesel transit bus
Number of vehicles: 2
Location: Tacoma, WA
Goal of application: Demonstration project
Participant: Pierce Transit
Sponsors: Washington Natural Gas Company, Pierce Transit
Source: American Gas Association

Type of vehicle: Transit bus
Number of vehicles: 2
Location: Los Angeles, California
Goal of Application: UMTA demonstration project
Participant: Southern California Regional Transit District
Source: American Gas Association

TABLE 2-1

Existing CNG Heavy-Duty Vehicle Applications (con't)

Type of vehicle: Transit bus
Number of vehicles: 2
Location: New York City
Goal of application: CNG bus demonstration program begun by New York City's Department of Transportation and the Department of Environment Protection
Participant: Command Bus Company
Sponsors: Brooklyn Union Gas Company provided engines; partial funding from UMTA
Source: American Gas Association, Natural Gas Vehicle Coalition

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Type of vehicle: Trash collection truck
Number of vehicles: 1
Location: New York City
Goal of application: Demonstration program
Participant: Department of Sanitation
Sponsor: Brooklyn Union Gas Company
Source: Natural Gas Vehicle Coalition

Type of vehicle: Delivery trucks (UPS)
Number of vehicles: 10
Location: New York City
Goals of application: Demonstration program
Participant: United Parcel Service
Sponsor: Brooklyn Union Gas Company
Source: Natural Gas Vehicle Coalition

Type of vehicle: Dual-fueled trucks
Number of vehicles: 2
Location: Minneapolis-St. Paul, MN
Goal of application: Demonstration program
Participant: Twin Cities Metropolitan Transit Authority
Sponsor: Minnegasco
Source: American Gas Association

Table 2-1 (cont'd)

Existing CNG Heavy-Duty Vehicle Applications

Type of vehicle: Gasoline-fueled school bus
Number of vehicles: 122
Location: Garland, TX
Goal of application: Economics
Participant: Garland, TX School District
Sponsor: Unknown
Source: Transportation Department and Garland Independent School District, "Compressed Natural Gas System, Two-Year Summary," June 1985.

Type of vehicle: School bus
Number of vehicles: 24
Location: Tulsa, OK
Goal of application: Economics
Participant: Tulsa, Oklahoma School District
Sponsor: Oklahoma Natural Gas Company
Source: American Gas Association

Type of vehicle: School bus
Number of vehicles: 90
Location: Indiana
Goal of application: Economics
Participant: Evansville & Vanderburg School Corporation
Sponsor: Not available

Type of vehicle: School bus
Number of vehicles: 40
Location: Erie, Pennsylvania
Goal of application: Economics
Participant: Harbor Creek School District
Sponsor: Not available

TABLE 2-1

Existing CNG Heavy-Duty Vehicle Applications (con't)

Type of vehicle: Dual-fuel CNG/diesel dump-trucks
Number of vehicles: 18
Location: Columbus, OH
Goals of application: Economics
Participant: Columbia Gas Corporation
Sponsors: Not applicable
Source: American Gas Association

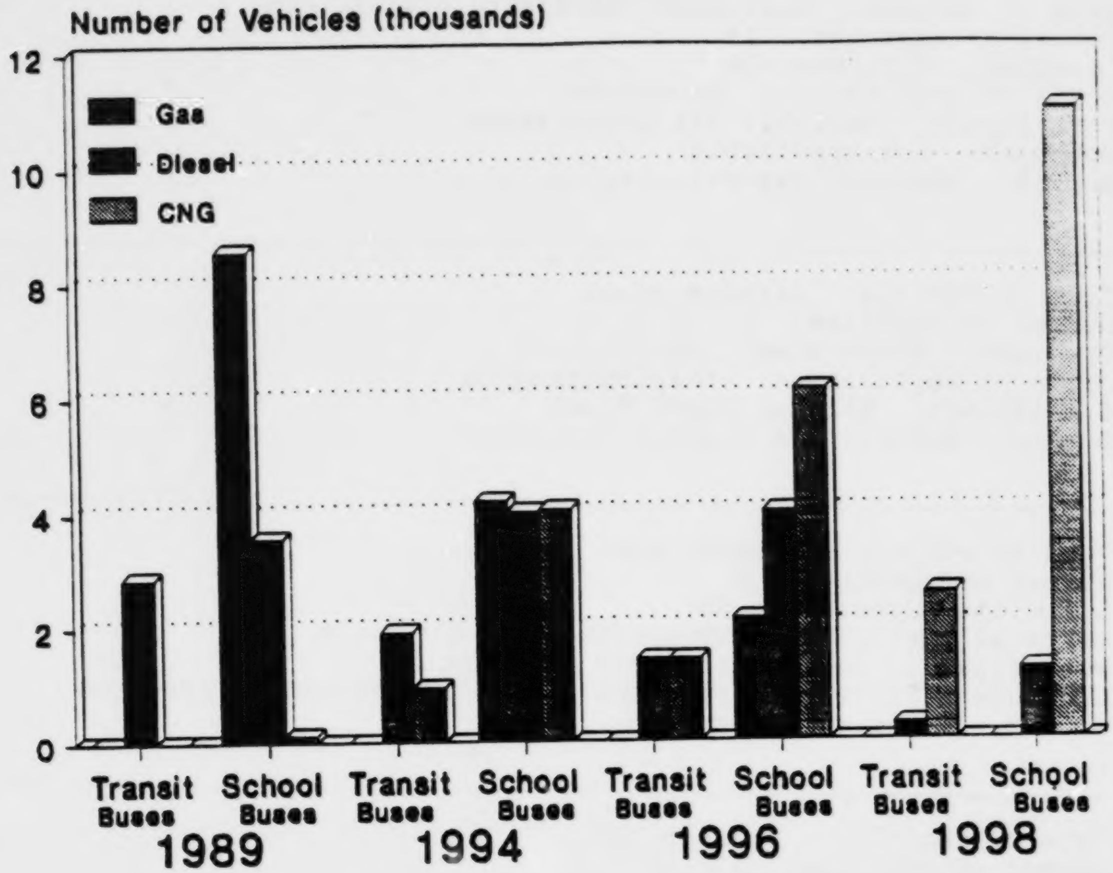
Type of vehicle: Garbage truck
Number of vehicles: 2
Location: North Miami, FL
Goals of application: Testing program
Participant: City of North Miami
Source: Natural Gas Vehicle Coalition

Type of vehicle: Transit bus
Number of vehicles: 1
Location: Cleveland, OH
Goals of application: Environmental, Economic
Participant: Consolidated Gas Corporation
Sponsors: Flxible Corporation, Consolidated Gas Corporation
Source: Flxible Corporation

Type of vehicle: Transit bus
Number of vehicles: 1
Location: Columbus, Ohio
Goals of application: Environmental, Economic
Participant: Central Ohio Transit Authority
Sponsors: Columbia Gas Company; Flxible Corporation
Source: Flxible Corporation

FIGURE 2-3

Projected Use of CNG Buses In Texas *



Legislative Implementation Schedule

* Texas Senate Bill 763 requires the use of CNG, or other alternative fuels that reduce emissions, to be used in rapid transit buses and, if necessary, certain local government and private fleet vehicles in non-attainment areas. Conversions of school buses as well as other fleets may not be necessary if Texas' 4 non-attainment areas (Dallas-Fort Worth, Houston-Galveston-Brazoria, Beaumont-Port Arthur, and El Paso) reach and maintain required attainment levels.

Source: The Economic Costs and Benefits of Proposed Amendments to the Texax Clean Air Act, the State Purchasing and General Services Act, the Metropolitan Rapid Transit Authority Act, the Regional Transportation Authority Act and the City Transportation Department Act, prepared for Texas General Land Office, March 1989.

CNG conversions of gasoline or diesel fuel systems (dual-fuel vehicles*) and moving into CNG-specific fuel systems and engines (i.e., dedicated vehicles). The initial conversions were from gasoline vehicles to dual-fuel vehicles. Gasoline conversions to dual-fueled vehicles are no longer under such active consideration, however, because such vehicles do not offer the cleanest or most fuel-efficient alternative, as will be discussed in Chapter 3. Most gasoline conversions today are to dedicated CNG vehicles.

Complications with the diesel engine have historically limited diesel conversions to primarily bi-fuel applications. Recent efforts by various gas utilities (e.g., Columbia Gas Co., Brooklyn Union Gas Co., Southwest Gas Corp.) have resulted in the successful conversions of 2-stroke diesel buses to bi-fueled vehicles, and a 4-stroke diesel bus to bi-fuel. These prototypes have proven that the conversions could be accomplished and that the characteristic black smoke from older diesel-fueled vehicles could be eliminated.** Diesel conversions to dedicated vehicles, however, look more promising in the long run, with the advent of the Cummins NG L 10 engine, which is derived from an existing Cummins diesel engine. Already being tested in buses, the Cummins design is able to meet the 1991 bus emissions standards.[3]

III. Potential Future Market for CNG Heavy-Duty Vehicles

The heavy-duty CNG market currently appears to be undergoing a resurgence of interest. There are about 170 confirmed CNG vehicles that have been contracted or planned for the near future. Many of these vehicles involve diesel buses that will be converted to dedicated CNG use using the Cummins NG L 10 engine. Table 2-2 briefly describes the future projects which have been identified. Some of these projects are partially funded by UMTA. UMTA is providing grants totaling $35.1 million to purchase buses that run on alternative fuels; approximately 20 percent is earmarked for CNG-fueled buses (although 80 percent of the applications received have been for CNG).

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* The term "dual-fuel" is used to refer to both a fuel system that enables the user to switch back and forth between CNG and gasoline use using a manual switch, as well as to CNG/diesel engines (sometimes called bi-fuel), which idle on 100 percent diesel and run on 80 percent CNG/20 percent diesel. This term should not be confused with what are commonly called "flexible fuel" vehicles. These latter vehicles, which operate on liquid alternative fuels, have the ability to inter-mix fuels in the same fuel tank. In contrast to this, CNG, being gaseous, requires its own distinct fuel storage and delivery system.

** Given both the difficulty of 2-stroke engine conversion and the presence in the exhaust of increased unburned fuel, the technological focus currently is on converting 4-stroke diesel engines.

Besides basic economic factors, the future market for CNG use in heavy-duty vehicles is also dependent on the parameters of the regulatory environment surrounding use of alternative fuels. Depending on the particular requirements in the final version of the Clean Air Act amendments, and implementation of the 1991 and 1994 emissions standards for buses and trucks, the potential size of the CNG market could grow significantly.

The President's proposed amendments also include a plan to require the use of clean alternative fuels in new urban buses in all cities with a 1980 population of over 1 million. This proposal would affect over 80 percent of all new bus purchases by the mid-1990s. Given the current high level of interest in CNG applications for buses, this would appear to be a promising market for CNG.

More broadly, CNG appears to be a readily adaptable fuel for a variety of heavy-duty uses. Heavy-duty vehicles generally have sufficient space available for CNG fuel cylinder placement and, as will be seen in subsequent portions of this report, are not greatly affected by the added weight of the fuel cylinders. CNG appears especially suited to those heavy-duty applications which have access to central fueling stations and would not require development of a significant fuel delivery infrastructure. Thus, promising areas for potential increased future use of dedicated CNG heavy-duty vehicles include many municipal applications such as school and transit buses, delivery trucks, and trash collection trucks. Other centrally fueled applications also exist in the private sector for such areas as utility service vehicles, local delivery trucks, etc. Dual-fueled vehicles may see even broader usage than this because of their ability to operate on both CNG and conventional fuel. However, as noted earlier, most current interest seems to be directed at dedicated vehicle development.

TABLE 2-2

New CNG Heavy-Duty Vehicle Projects

Type of vehicle: CNG-dedicated transit bus
Number of vehicles: 1
Location: Phoenix, AZ
Participant: Phoenix Transit
Sponsor: Southwest Gas Corporation
Comments: Southwest Gas has given the "okay" to order the Cummins engine for the bus; Southwest Gas will lease bus at no cost to Phoenix Transit for one or two years.
Source: Southwest Gas Corporation

Type of vehicle: Trash collection trucks
Number of vehicles: 8
Location: New York City/Staten Island
Participant: Snug Harbor Cultural Center
Sponsor: Brooklyn Union Gas Company
Comments: None
Source: Natural Gas Vehicle Coalition

Type of vehicle: Heavy-duty trucks
Number of vehicles: 50
Location: New York City
Participant: NYC Department of Parks
Sponsor: Brooklyn Union Gas Company
Comments: None
Source: Brooklyn Union Gas Company

Type of vehicle: Postal vehicles
Number of vehicles: 50
Location: New York City/Staten Island
Participant: Post Office
Sponsor: Brooklyn Union Gas Company
Comments: None
Source: Brooklyn Union Gas Company

TABLE 2-2

New CNG Heavy-Duty Vehicle Projects (con't)

Type of vehicle: Transit bus
Number of vehicles: 10
Location: Southern California
Participant: Southern California Transit Districts
Sponsor: Flxible Corporation
Comments: Contract is on back-order because of performance testing to be conducted on existing converted buses and the volume of conversion contracts.
Source: Flxible Corporation

Type of vehicle: Transit bus
Number of vehicles: 3
Location: Fort Worth, TX
Sponsor: Flxible Corporation
Comments: Contract is on back-order because of performance testing to be conducted on existing converted buses and the volume of conversion contracts
Source: Flxible Corporation

Type of vehicle: Transit bus
Number of vehicles: 2
Location: Dallas, TX
Sponsor: Not available
Comments: Contract is on back-order because of performance testing to be conducted on existing converted buses and the volume of conversion contracts.
Source: Flxible Corporation

Type of vehicle: Transit bus
Number of vehicles: 5
Location: New Jersey
Sponsor: Not available
Comments: Contract is on back-order because of performance testing to be conducted on existing converted buses and the volume of conversion contracts
Source: Flxible Corporation

TABLE 2-2

New CNG Heavy-Duty Vehicle Projects (con't)

Type of vehicle: Transit bus
Number of vehicles: 2
Location: Los Angeles, CA
Participant: L.A. County Transportation Commission
Sponsor: Southern California Gas Company
Comments: None available
Source: American Gas Association

Type of vehicle: Transit bus
Number of vehicles: 5
Location: Rochester, NY
Participant: Rochester-Genesee Regional Transportation Authority
Sponsor: UMTA (75% of cost)
Comments: None available
Source: Rochester Gas & Electric, Rochester, New York

Type of vehicle: Transit bus
Number of vehicles: 23
Location: Buffalo, Syracuse, and Long Island, NY
Participants: Transit authorities in Buffalo, Syracuse, and Long Island, NY
Sponsor: UMTA (75% of cost)
Comments: Buffalo, Syracuse, Long Island, and Rochester (see previous entry) transit authorities are involved in a group purchase of 28 natural gas-fueled transit buses. UMTA assistance totaling $6.3 million will pay for 75% of the cost, with state and local funds providing a 25% share.
Source: Department of Transportation

Type of vehicle: Transit bus
Number of Vehicles:
Location: Tacoma, Washington
Participant: Pierce Transit
Sponsor: UMTA ($8.3 million)
Source: New York Times, March 1989

References Chapter 2

1. Pietro Magistris, "Compressed Natural Gas Distribution System in Italy," in Symposium Papers: Nonpetroleum Vehicular Fuels II, presented in Detroit, Michigan, June 15-17, 1981.

2. American Gas Association, "Natural Gas Vehicles Bulletin," Cat. No. G92238, 1989.

3. Conversation between ICF Incorporated and Jeff Seisler, Natural Gas Vehicle Coalition, October 1989. Phase I engine tested at Southwest Research Institute with oxidation catalyst.

4. Gross and Weinstein, "The Economic Costs and Benefits of Proposed Amendments to the Texas Clean Air Act, the State Purchasing and General Services Act, the Metropolitan Rapid Transit Authority Act, the Regional Transportation Authority Act, and the City Transportation Department Act" for the Texas General Land Office, March 1989.

CHAPTER 3

CNG HEAVY-DUTY VEHICLE TECHNOLOGY

I. Introduction

In this chapter the hardware, emissions and performance of heavy-duty CNG vehicles will be discussed. First, a brief discussion of the properties of natural gas as a vehicle fuel will be presented, followed by a description of the hardware on current dual-fuel and dedicated CNG vehicles. Next, the emissions and performance of current technology will be presented. Finally, projections of the emissions and performance of future optimized dedicated CNG engines will be derived. The emissions information presented here will be used in Chapter 5 for a comparison of the environmental impacts of heavy-duty CNG vehicles and their gasoline and diesel counterparts.

II. Fuel Properties of Natural Gas

The most fundamental difference between natural gas and conventional motor fuels (i.e., gasoline, diesel fuel) is that natural gas, unless cryogenically stored (i.e., at extremely low temperatures) under pressure, is in gaseous form rather than a liquid. As can be seen from the fuel properties in Table 3-1, the energy density (Btu/gal) of natural gas as it is stored on a vehicle is very low compared to liquid fuels. This has significant impacts in the area of onboard fuel storage as will be discussed shortly.

The composition of natural gas varies, as can be seen from Table 3-1. The methane content of natural gas is typically over 90 percent although it can be lower. This results in unburned hydrocarbon (HC) emissions that are largely methane, as will be seen later. In terms of ozone forming potential, methane is essentially unreactive. Thus, on a mass basis, CNG HC emissions are much less ozone forming that the HC emissions from gasoline and diesel engines. This is discussed further in Chapter 5.

Two of the more important properties of fuels in relation to engine design are the octane and cetane ratings. The octane rating of a fuel is a measure of its resistance to knock (spontaneous combustion away from the spark-initiated flame front). Good antiknock properties are important in spark ignited engines because they allow for increased compression ratios and a resultant increase in engine efficiency. As is shown in Table 3-1 the octane rating of natural gas is significantly higher than for gasoline.

Table 3-1

Properties of Natural Gas and Conventional Petroleum Fuels

Properties	Commercial Unleaded Gasoline	No. 2 Diesel Fuel	Typical CNG
Chemical Constituents	Mixture of Hydrocarbons (chiefly C_4 -C_{10})	Mixture of Hydrocarbons (chiefly C_{12} -C_{20})	90-98% Methane Remainder, Ethane and Other Paraffins, CO_2, H_2, He, N_2
Boiling Range (°F @ 1 atm)	80 to 420	320 to 720	-259*
Specific Gravity	0.71 to 0.78[2]	0.79 to 0.88**	0.13***
Btu/ft^3 of Mixture (LHV)	95.5****	96.9****	87.0****
Btu/gal (LHV)	114,132	129,400	19,760 @ 2400 psi 70°F
Btu/lb (LHV)	18,900	18,310	21,300
Octane Number $\frac{(R+M)}{2}$	87-93	N/A	120*****
Cetane Number Range	5-20	38-51	N/A
Stoichiometric Air/Fuel Ratio (weight)	14.5 to 15.5	14.5 to 15.1	17.2
Peak Flame Temp (°F)	3900-4100	---	3410

---

* Pure Methane. Other minor constituents (ethane, propane, etc.) boil at higher temperatures.

** At 60°F with respect to water at 60°F.

*** At 80°F with respect to water at 60°F.

**** At stoichiometric gaseous air/fuel ratio, 14.7 psia, 60°F, lower (net) heating value.

***** Octane number ratings above 100 are correlated with given concentration of tetraethyl lead in iso-octane.

Source: EA-Mueller, Inc. and "Gaseous Fuel Safety Assessment for Light-Duty Automotive Vehicles," M.C. Krupka, A.T. Peaslee, and H.L. Laquer, Las Alamos National Laboratory, November 1983.

The cetane rating of a fuel is a measure of its ability to autoignite when compressed and heated. A high cetane fuel is essential for the proper operation of a compression ignition (i.e., diesel) engine where no external ignition source is used. Although no actual cetane number is available for natural gas, its cetane rating is very low compared to diesel fuel. This is reasonable given that in a sense octane and cetane are opposites and natural gas has a very high octane rating. For this reason natural gas generally cannot be used in an internal combustion engine without an external ignition source (which could be a spark plug or a pilot injection of diesel fuel).

III. Current Heavy-Duty CNG Technology

A. Engines

As noted in Chapter 2, CNG has been used on a limited scale as a heavy-duty vehicle fuel for many years in the United States. Generally, a conversion kit consisting of fuel storage cylinders, high pressure fuel lines, fuel pressure regulation equipment and some type of fuel-air mixer has been retrofitted onto a vehicle originally designed to operate on some other fuel, usually gasoline. Most often the capability to operate on the original fuel was retained, giving rise to a dual-fuel vehicle which was clearly not optimized for CNG use.

The operation of gasoline-derived dual-fuel vehicles is somewhat different than for diesel-derived versions. Since gasoline engines already have a spark ignition system, the dual-fuel gasoline/CNG engines are designed for the use of only one fuel at a time and usually have a switch on the dashboard to allow the driver to choose which fuel to run on. In contrast to gasoline engines, diesel engines rely on compression of the charge to autoignite the fuel. Since natural gas has low cetane ratings, compression ignition is difficult to initiate and control and an external ignition source is required. Generally, in conversion situations, a pilot injection of diesel fuel is used to initiate combustion. With this type of conversion the engine retains the ability to run on pure diesel fuel or varying amounts of natural gas replacing diesel fuel (up to 90 percent at high loads) but not on pure natural gas.[1] In any case, as will be described further below, to date very little effort has gone into accurately characterizing the emissions, performance, or the long term durability of converted heavy-duty CNG powered vehicles.

Only recently has serious effort been directed at developing heavy-duty vehicle engines dedicated and optimized for CNG, taking advantage of the unique qualities of natural gas as a vehicle fuel. In this regard, there are two distinct approaches being used, which this report will characterize as "lean-burn combustion" and "stoichiometric combustion." Lean-burn combustion engines have been derived from current diesel engines, which operate with a substantial amount of excess air in the combustion chamber, giving rise to the lean-burn designation. The stoichiometric approach, which utilizes a chemically correct fuel-air mixture with no excess air, has been derived from gasoline-fueled engine designs using a three-way catalyst control system. Such engines must operate very close to ideal, stoichiometric, air-fuel mixtures for the three-way catalyst to perform properly.

Each of these combustion systems has its advantages and disadvantages, and both are considered good candidates for more widespread use in various heavy-duty vehicle applications. Although both are spark-ignited, homogeneous charge combustion systems, their engine-out emissions and catalyst strategies are different and result in characteristically different tailpipe emissions. Since there are characteristic differences in both engine hardware and emissions performance, the two designs will be evaluated separately in this report. Also, since the lean-burn combustion system is derived from and will most likely replace diesels in future uses, diesel engine performance will be the baseline for comparison with CNG lean-burn combustion engines. Similarly, evaluation of CNG stoichiometric combustion engines relative to current fuels will be based upon gasoline-fueled designs. Even though this convention will be carried through the rest of this report, it should be born in mind that there is no fundamental reason preventing the eventual crossover of future applications of lean-burn and stoichiometric combustion designs.

It is also worth noting at this point that there are different emissions testing cycles for current diesel and gasoline-fueled heavy-duty engines. These cycles are used to reflect the characteristic differences between typical usage patterns for these engines. When comparing emissions between lean-burn and stoichiometric CNG combustion designs, a single cycle will be used for both, to insure compatible results. The diesel cycle has been chosen for this purpose because it is the only cycle for which data on both designs exists. The evaluation of environmental benefits in Chapter 5, however, will be based upon the diesel cycle when comparing to conventional diesel engines, and the gasoline cycle when comparing to conventional gasoline-fueled engines.

As just noted, the lean-burn dedicated CNG engines currently being developed are based on existing diesel engines. They are usually run at a relative fuel-air ratio of around 0.7, although fuel-air ratios well below this have been demonstrated by Southwest Research Institute using a prechamber with a stoichiometric spark-ignited charge and a very lean mixture in the main chamber.[2] This latter approach holds promise to improve the efficiency/NOx tradeoff associated with lean-burn engines. In general the open combustion chamber approach utilizes intake throttling for power control. The prechamber approach is unthrottled except at idle and relies upon control of the amount of fuel being metered into the chamber through check valves for power control. In either case the low cetane number of natural gas means a strong spark is needed for ignition in dedicated CNG engines.

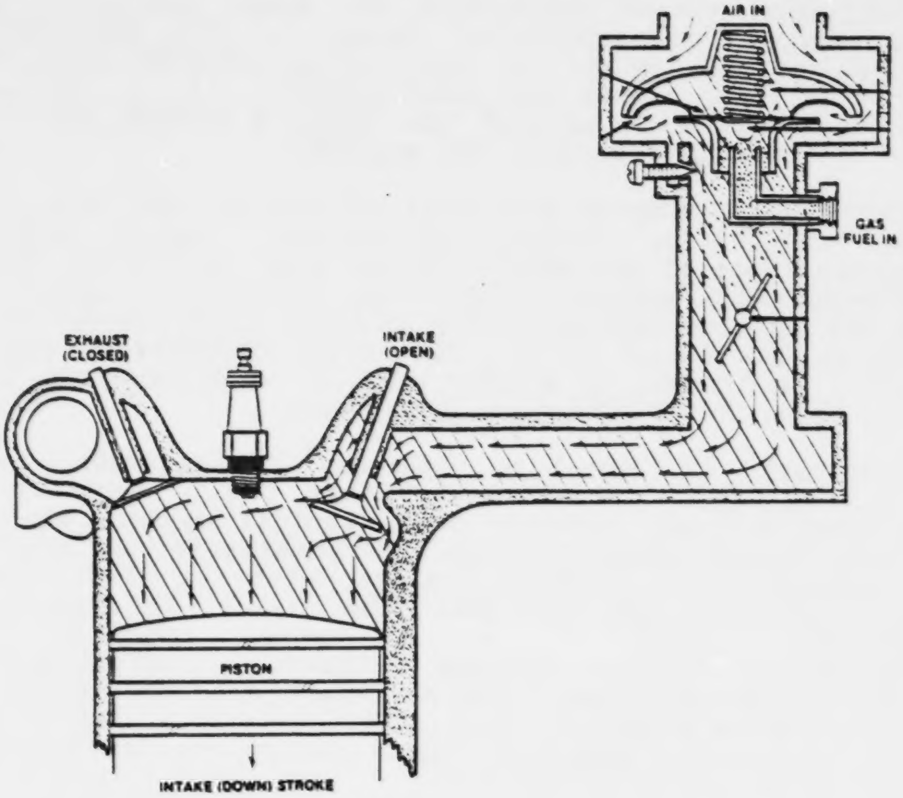
Although the antiknock qualities of natural gas are very good, the compression ratios of current diesel engines (approximately 19 to 1) are generally too high to prevent knock in a dedicated CNG engine. Thus, the compression ratios in lean-burn CNG engines are generally reduced to below 15 to 1 and can be as low as 10 to 1. The lowest compression ratios are conservative designs to account for the wide range of fuel composition which the engine might see in-use.

In contrast to lean-burn engines, stoichiometric CNG engines are generally based on gasoline engine technology. They have used a 3-way catalyst based control system, with or without the closed loop controls characteristic of current gasoline engines. The relative fuel-air ratio is ideally held extremely close to one so that the 3-way catalyst can simultaneously oxidize THC and CO while reducing NOx. Throttling of the fuel-air mixture is used to control power. As was previously mentioned, the antiknock characteristics of natural gas are much better than gasoline. As a result the compression ratio of a gasoline engine can be boosted somewhat when converted to dedicated CNG use.

The fuel-air mixer is a central component in any CNG engine configuration. The mixer serves the same function on a CNG engine as a carburetor or fuel injectors on conventional engines, i.e., metering the fuel into the air at the proper fuel-air ratio for proper operation. Precise control of the fuel-air ratio over the entire speed and load range of the engine is essential in achieving good performance, fuel economy and emission characteristics.

Common mixer designs today are generally mechanical in nature and meter the fuel as a function of intake air pressure. A common mixer design is shown in Figure 3-1. In addition to this spring-loaded diaphragm variety, venturi based mixers are also available. These current technology mixers are

Figure 3-1


AIR IN
GAS FUEL IN
EXHAUST (CLOSED)
INTAKE (OPEN)
PISTON
INTAKE (DOWN) STROKE

Diaphragm Operated Air-Gas Mixer

Source: IMPCO Master Catalog, 1987

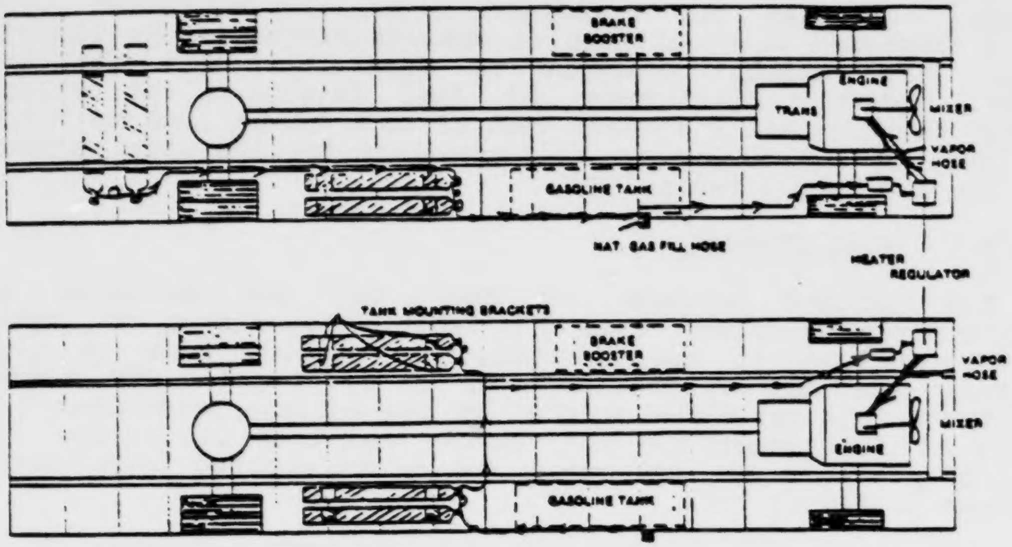
not nearly as sophisticated as the fuel metering equipment on today's conventional engines. The less developed nature of CNG technology in conjunction with the difficulty in general of precisely metering a gas combine to produce current CNG engines which do not have the precise control of fuel-air ratios needed to truly optimize performance and emissions. Although much progress is being made in the area of fuel metering for CNG engines, including the introduction of simple closed loop control systems, which utilize an exhaust oxygen sensor (lambda sensor) and feedback controls to maintain proper fuel-air ratios, and the development of fuel injection to replace mixers, there is still a great deal of work to be done to bring the level of CNG fuel metering technology in line with current gasoline and diesel technology.

B. Fuel Storage

The onboard storage of fuel for CNG vehicles is significantly different than for vehicles operating on liquid fuels. The natural gas is stored in gaseous form in high pressure cylinders at pressures up to 3,000 psi. The number and size of the cylinders mounted on the vehicle determines the amount of fuel stored on the vehicle and thus its range. On heavy-duty trucks the cylinders are often mounted underneath, as shown in Figure 3-2.

Currently, the weight and bulk of CNG cylinders is a concern with CNG vehicles, both in terms of available space for storage and reduced performance and fuel economy due to increased weight. However, this concern appears to be primarily related to light-duty applications and does not appear to present as much difficulty in the heavy-duty area. Conventional steel cylinders filled with natural gas weigh roughly five times more than diesel or gasoline tanks and fuel on an energy equivalent basis. Also, a given volume of natural gas at 3000 psi contains only about one fifth of the energy of the same volume of diesel fuel.[3] The effect this has on the weight and range of heavy-duty vehicles depends a great deal on the application. As will be shown in Chapter 5, putting enough storage capacity on a heavy-duty vehicle for it to have equivalent range on CNG as its gasoline or diesel counterpart increases vehicle weight 6.5-9.4 percent. In many applications this is not a problem. However, for transit buses increased weight may result in a de-rating of the passenger carrying capacity of the bus. Thus, there is a trade-off between weight penalty and vehicle range which must be examined for each application. Finally, CNG fuel tanks are presently constrained to cylindrical shapes and do not offer the packaging flexibility that is available with liquid fuels.

Figure 3-2


BRAKE BOOSTER
ENGINE
TRANS
MIXER
VAPOR HOSE
GASOLINE TANK
NAT GAS FILL HOSE
HEATER
REGULATOR
TANK MOUNTING BRACKETS
BRAKE BOOSTER
VAPOR HOSE
MIXER
ENGINE
GASOLINE TANK

Typical Mounting Locations For CNG Cylinders
on School Buses and Medium-Duty Trucks

Source: Nu-Fuels, Inc.

Although most cylinders currently being used are of the plain steel variety, lighter weight designs including fiber-wrapped steel and fiber-wrapped aluminum are beginning to see some commercial use. Advanced all-composite cylinders are also being developed. These designs offer much improvement in the weight to energy ratio over plain steel cylinders as is shown in Figure 3-3. However, Figure 3-3 shows that even the best designs still have a 2:1 weight disadvantage compared to gasoline and diesel fuel. Since this weight penalty arises from the storage cylinders and not the fuel itself, the area of fuel storage system weight and bulk reduction, through the use of increasingly lighter materials to reduce weight and adsorbent technology to reduce needed storage volume and/or pressure, is an area where additional work can yet be done to improve the attractiveness of CNG as an alternative to conventional motor fuels.

Natural gas may also be stored onboard as a cryogenic liquid (LNG). The resultant improvement in the volumetric energy content of LNG as compared to CNG may result in improved range or performance due to lower storage weight and volume per unit of energy stored. However, because natural gas liquifies at -259°F, the onboard storage vessels must be well insulated. Even then an unused vehicle must vent boiloff gas periodically. While this has been reported to be as frequent as every 7-8 days[4], the American Gas Association indicates that current LNG vehicles can hold LNG without boiloff for up to three weeks. The costs associated with liquifaction, refueling, and storage hardware for LNG make it less attractive at present, although this could change with advances in technology and changes in fuel economics. The vast majority of natural gas powered vehicles today have fuel stored in compressed, rather than liquified form. Therefore, this report will only address CNG.

C. Emissions From Current Technology CNG Vehicles

1. Dual-Fuel Vehicles

The actual emissions of current technology CNG-powered heavy-duty engines are not well characterized and there is only an extremely limited amount of transient emission test results available.* Turning first to dual-fuel vehicles, EPA is not

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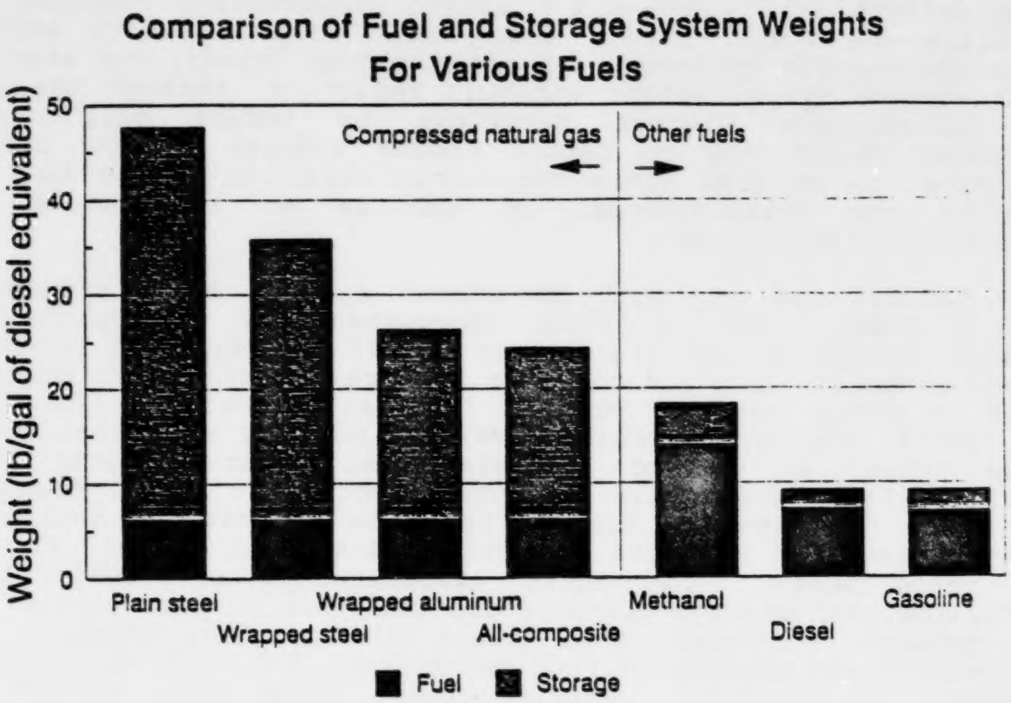
* The EPA heavy-duty transient test (as defined in the U.S. Code of Federal Regulations, Title 40, part 86) is the standard engine test for heavy-duty engine emissions certification. The engine is placed on an engine dynamometer and run through a standardized test cycle which simulates in-use engine operation.

Figure 3-3



Source: "Natural Gas Vehicles: A Review of the State of the Art", Sierra Research Report No. SR89-04-01, April 1989.

aware of any heavy-duty transient testing ever performed on a dual-fuel retrofit engine. Presumably, conclusions can be drawn, at least for stoichiometric heavy-duty gasoline/CNG dual-fuel engines, based on limited testing of similar light-duty dual-fuel vehicles. These results show that the vehicle's operation on CNG can yield large reductions in CO and the same or somewhat lower non-methane HC compared to operation on gasoline. However, CNG also yields somewhat higher NOx and much higher methane emissions compared to gasoline.[5] Also, the emissions can vary a great deal depending on the quality of the conversion and the state of tune the vehicle is in. Reductions in CO are by no means guaranteed, as is evidenced by testing of three light-duty dual-fuel retrofit vehicles done at the EPA Motor Vehicle Emission Laboratory. Two of the three vehicles tested in as received condition had CO emissions two to eight times higher on natural gas than on gasoline. Subsequent recalibration and maintenance, however, yielded a substantial CO benefit.[5]

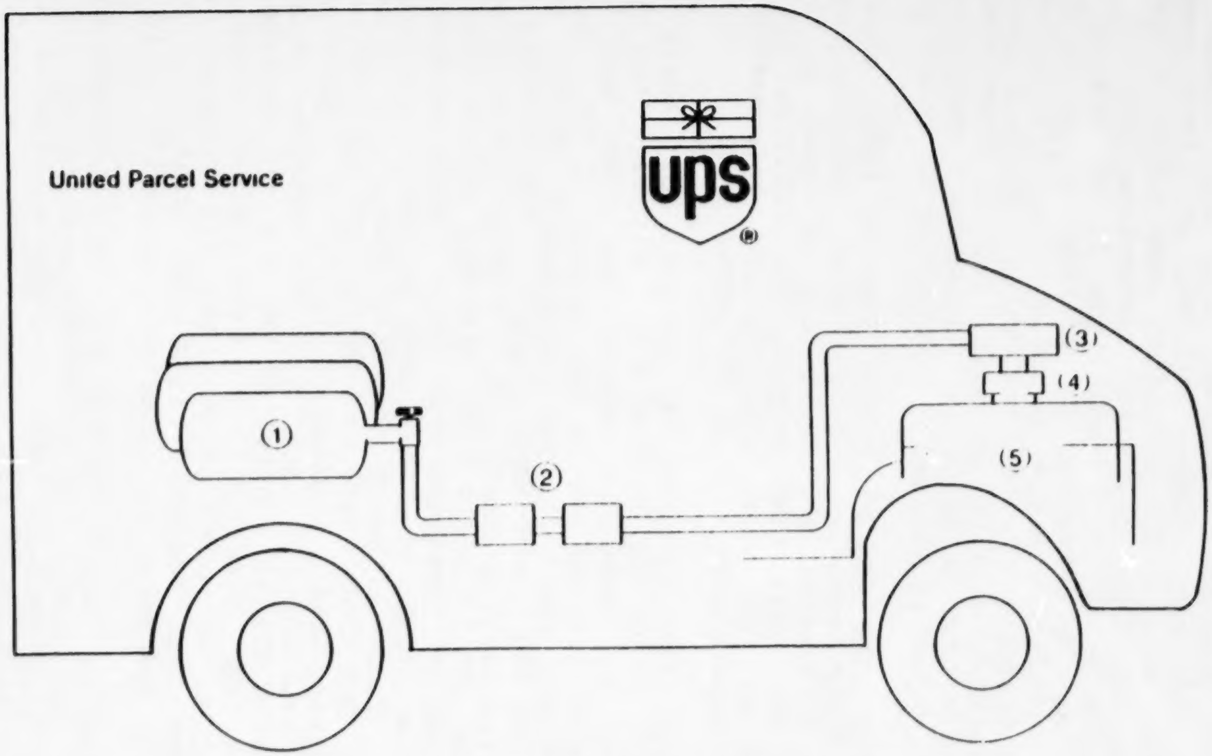
Recently, the United Parcel Service (UPS) converted ten parcel delivery vehicles to dual-fuel gasoline/natural gas operation. A diagram of the vehicle is shown in Figure 3-4. During the two year UPS program the vehicles will be run exclusively on CNG when possible and information on fuel economy and maintenance will be collected.

Emission testing results of one of these converted vehicles are shown in Figure 3-5. Although the data shows emissions to be lower on natural gas than gasoline, these results are of limited use in the context of this study for two reasons. First, the test cycle used was a chassis dynamometer test in which the whole vehicle was run over a cycle simulating New York City driving conditions. This means that comparisons between the UPS vehicle and engines tested over the EPA heavy-duty engine transient test cycle cannot be made. Second, no baseline data of the vehicle before conversion is available. Thus, although the data shows the vehicle to be cleaner on CNG than gasoline, it is unknown what effect, if any, conversion had on gasoline emissions. Past testing on light-duty vehicles has shown that the addition of a dual-fuel CNG conversion kit to a gasoline vehicle can degrade emissions performance on gasoline.[6] Nevertheless, the data is interesting as a reference and the UPS program promises to provide some much needed data on the durability, maintenance requirements and emissions deterioration of CNG vehicles.

Turning to lean-burn dual-fuel CNG engines with diesel fuel pilot ignition, the emission benefits of this type of system are also unclear. Steady-state testing of a converted Caterpillar 3406 large truck engine with electronic injection

Figure 3-4

UPS NATURAL GAS CONVERSION


United Parcel Service
ups
(1)
(2)
(3)
(4)
(5)

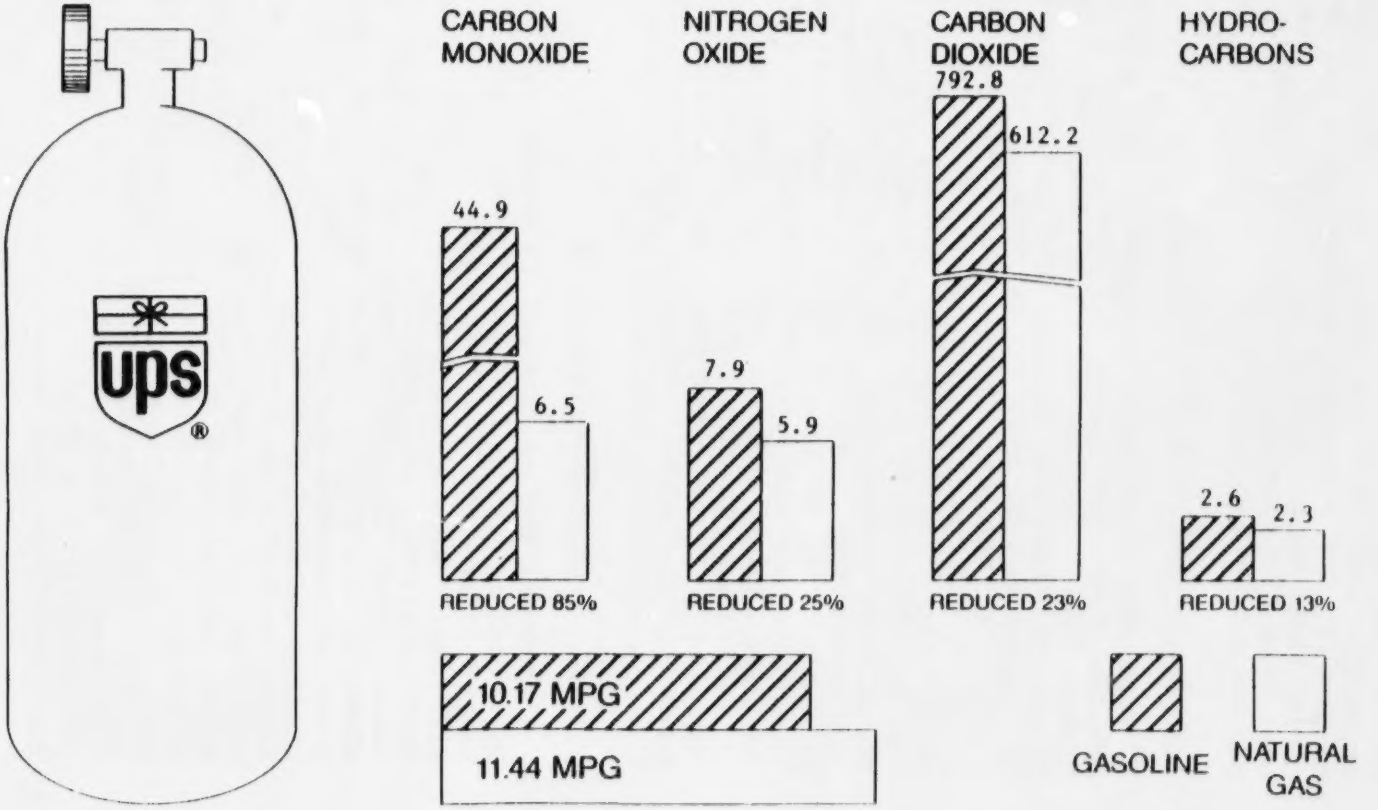
(1) THREE NATURAL GAS CYLINDERS EQUALING 15 GALLONS
(2) TWO REGULATORS TO REDUCE PRESSURE
(3) NATURAL GAS-AIR MIXER
(4) GASOLINE CARBURETOR
(5) GASOLINE ENGINE

SOURCE: UNITED PARCEL SERVICE / BROOKLYN UNION GAS COMPANY

Figure 3-5

EMISSIONS OF UPS PACKAGE CAR WHILE MOVING

(grams per mile)



SOURCE UNITED PARCEL SERVICE / BROOKLYN UNION GAS COMPANY of both CNG and the diesel pilot showed mixed results, with a reduction in NOx, little or no effect on HC and particulate, and a significant increase in CO.[1] With little useful emissions data on these types of conversions, it is difficult to predict any emissions benefit with any assurance and it is clear that more testing of heavy-duty dual fuel conversions must take place before any emission benefits attributed to them can be accurately quantified.

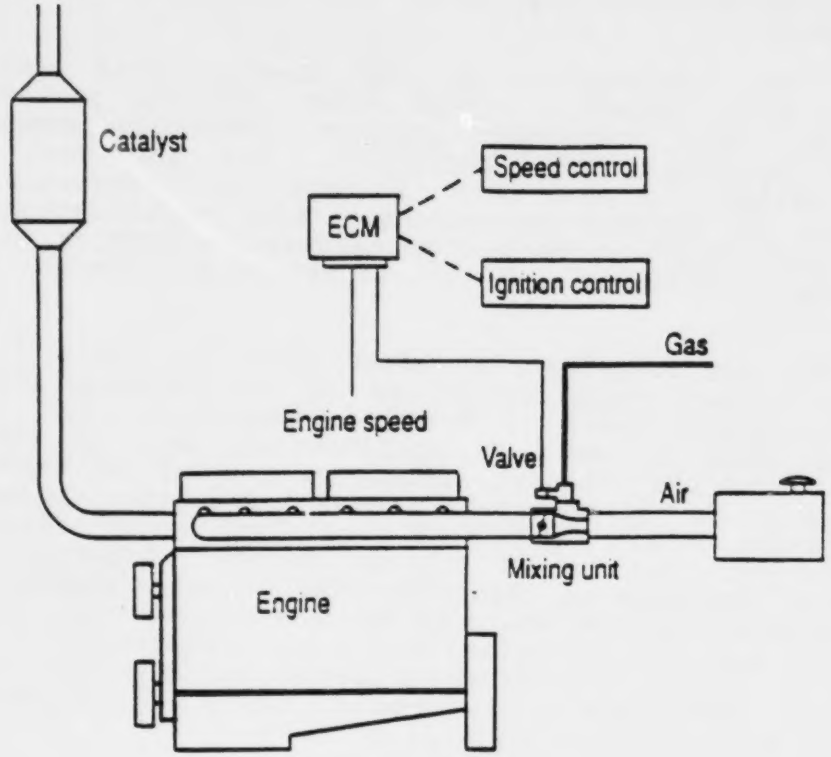
2. Dedicated CNG Vehicles

As was previously discussed, the properties of CNG as a vehicle fuel are quite different from those of gasoline or diesel fuel. Because of this, dual-fuel CNG engines cannot be fully optimized for natural gas operation, because compromises in engine design have to be made in order to operate on both fuels. At the same time, dual-fuel vehicles clearly have a place in the transition to clean alternative fuels because they offer the flexibility to operate on conventional and CNG fuels. This ability will be especially valuable in easing the transition to dedicated CNG use while the CNG refueling station infrastructure is further developed. However, due to the lack of substantial emissions data on dual-fuel engines, this report is not in a position to quantify the benefits of dual-fuel vehicles (other than to say that they will be less than those of dedicated vehicles) and will focus principally on dedicated vehicles. Since lean-burn and stoichiometric engines have somewhat different emission characteristics they will be treated separately, beginning with lean-burn.

a. Lean-Burn Combustion

Cummins Engine Company is presently developing a dedicated CNG version of its L-10 heavy-duty diesel engine for commercial introduction into the bus engine market in 1991. To date, two different configurations have been tested. The first configuration utilizes a mechanical diaphragm mixer manufactured by IMPCO Carburetion, Inc. similar to the one shown in Figure 3-1. This system has separate idle and full power adjustments but is an open-loop (i.e., one which does not utilize feedback from an exhaust sensor for automatic fuel-air ratio control) mechanical system. The second configuration utilizes an open-loop electronically controlled venturi-type mixer manufactured by TNO Road Vehicles Research Institute in Holland. A diagram of a similar system is shown in Figure 3-6. Both configurations utilize intake throttling for power control and an oxidation catalyst for HC control. Transient test results are not publicly available for the two CNG L-10 configurations. However, Cummins has released its emissions design targets, and based upon EPA's review of the confidential

Figure 3-6


Catalyst
Speed control
ECM
Ignition control
Gas
Engine speed
Valve
Air
Mixing unit
Engine

Open Loop Electronically Controlled Air/Fuel System
With Venturi-Type Mixer

Source: TNO Road-Vehicles Research Institute transient test data EPA is confident these targets will likely be met or exceeded. Cummins's design targets are shown in Table 3-2.[7]

Also included in Table 3-2 are emission results for a natural gas-fueled Caterpillar 3406. This engine also utilized an open-loop IMPCO system and had no catalyst.[8] It was developed for steady-state electrical cogeneration purposes and was not optimized for transient operation.[9] Nevertheless, these data are useful in analyzing emission trends of lean burn heavy-duty CNG engines, especially given the limited amount of data available.

Using the information on the Cummins L-10 and the Caterpillar 3406, emission levels which, for the purposes of this report, will represent current lean-burn combustion technology emissions were developed. For the most part, Cummins' design targets are assumed to represent the capabilities of current technology. Some modifications and additions were made to the design targets as Cummins did not specify CO_2, non-methane HC or formaldehyde levels in its targets.

The CO_2 and formaldehyde values shown in Table 3-2 for current technology were chosen to to be representative of current technology based on energy consumption data on the Caterpillar 3406 as well as confidential data on the L-10 engine emissions and catalyst efficiencies. The non-methane HC was assumed to be ten percent of total hydrocarbon, based upon the Caterpillar data. The use of a catalyst could affect this number somewhat, but to an unknown degree. Experience with conventional catalysts on light-duty CNG vehicles suggests that the non-methane fraction would be decreased. However, the L-10 CNG catalyst has been optimized for total hydrocarbon control, meaning that it has significantly better methane control than conventional catalysts. It would therefore affect the non-methane fraction much less, if at all.

Concerning the particulate emission level chosen to represent current technology, the Cummins design target was used even thought the Caterpillar engine showed particulate emissions ten times higher than this. There is no inherent reason why CNG should have high particulate levels in and of itself, given that fuel-derived particulate is generally attributed to heavy, long chain hydrocarbons which are not found in natural gas. The higher particulate rate on the Caterpillar engine has been attributed to lubricating oil passing the piston ring pack and entering the combustion chamber. This assumption was supported by the fact that the particulate was 90 percent soluble organics, generally

Table 3-2

Summary of Low Mileage Emissions From Lean-Burn CNG Engines Operated Over the EPA HDDE Transient Test Cycle (g/BHP-hr)

Pollutant	Cummins CNG L-10 Design Targets	Cat. 3406 w/o catalyst	1991 Diesel Standards	Assumed Current CNG Technology
THC	0.9	9.2	1.3	0.9
NMHC	---	0.84	---	0.09
NOx	4.5	4.1	5.0	4.5
Part.	0.06	0.60	0.25/0.10*	0.06
CO	4.0	3.2	15.5	4.0
CO_2	---	--	---	575
Formaldehyde	---	0.34	---	0.05

---

* The 0.10 standard applies to urban bus engines only. The 0.25 standard applies to all other heavy-duty diesel engines.

associated with lube oil. Improved oil control is a significant part of current efforts to reduce engine-out particulate levels for 1991 diesels, and low oil consumption designs have been successfully incorporated into diesel engines in these attempts. Thus, there is no reason to believe than lean-burn combustion CNG engines will have high particulate levels.

b. Stoichiometric Combustion

The only available transient engine emissions data for a dedicated stoichiometric heavy-duty CNG engine is shown in Table 3-3. This engine was built from a Chevrolet 454 gasoline engine and was converted to dedicated CNG use by Brooklyn Union Gas (BUG). This engine was tested at the EPA Motor Vehicle Emission Laboratory (MVEL) in Ann Arbor, MI. Although the results from two configurations are shown here, only the IMPCO mixer configuration was introduced into the two buses which are presently operating in New York and, thus, this engine was chosen to represent current stoichiometric technology. The hardware for the BUG engines is similar to that described for the Cummins L-10, with the addition of a lambda sensor in the exhaust stream of the TNO configuration for closed loop control of the stoichiometric fuel-air mixtures, as shown in Figure 3-7.

During the testing of the BUG engine at MVEL tests were run over both the diesel engine test cycle and the gasoline engine test cycle. Although these cycles are different, the results from both are useful and are shown in Table 3-3. The results from the diesel test cycle will be used to compare this engine to the lean burn CNG engine while the gasoline test cycle results will allow a direct comparison to the gasoline engine from which it was derived. This latter comparison will be discussed in Chapter 5 while the comparison of the stoichiometric and lean burn CNG engines will be discussed shortly.

One other point that should be mentioned with respect to the BUG data in Table 3-3 is that the with-catalyst results for the gasoline test cycle were hot start only, rather than composite results. Official transient test results are weighted six hot start tests to one cold start test and a composite result is arrived at. No cold start tests were performed on the gasoline test cycle with a catalyst and only the hot start results are shown in Table 3-3. However, the hot and cold start data for the without-catalyst tests were nearly identical. Given this fact together with the six to one hot to cold start ratio, the hot start results shown are assumed to represent composite results.

Table 3-3

Summary of Low Mileage Emissions From the Brooklyn Union Gas (BUG) Stoichiometric CNG Engine (g/BHR-hr)

Pollutant	IMPCO Mixer w/o Catalyst	IMPCO Mixer w/catalyst	TNO Mixer w/o catalyst	TNO Mixer w/catalyst	Applicable Standards
Diesel Test Cycle					
THC	3.6	1.03	3.57	1.01	1.3
NMHC	0.82	0.15	0.83	0.17	--
NOx	6.62	1.33	6.87	1.16	5.0
Part.	0.01	0.01	0.01	0.01	0.25/0.10
CO	31.9	10.8	23.3	6.64	15.5
CO_2	529	557	520	540	--
Formaldehyde	0.03	0.0008	0.02	0.0007	--
Gasoline Test Cycle**					
THC	1.7	0.72	1.47	0.84	1.1/1.9***
NMHC	0.40	0.09	0.34	0.12	--
NOx	5.75	0.51	6.57	1.46	5.0
Part.	0.01	0.01	0.05	0.01	--
CO	28.5	10.6	8.16	4.54	14.4/37.1***
CO_2	474	500	471	504	--
Formaldehyde	0.02	0.0001	0.02	0.0007	--

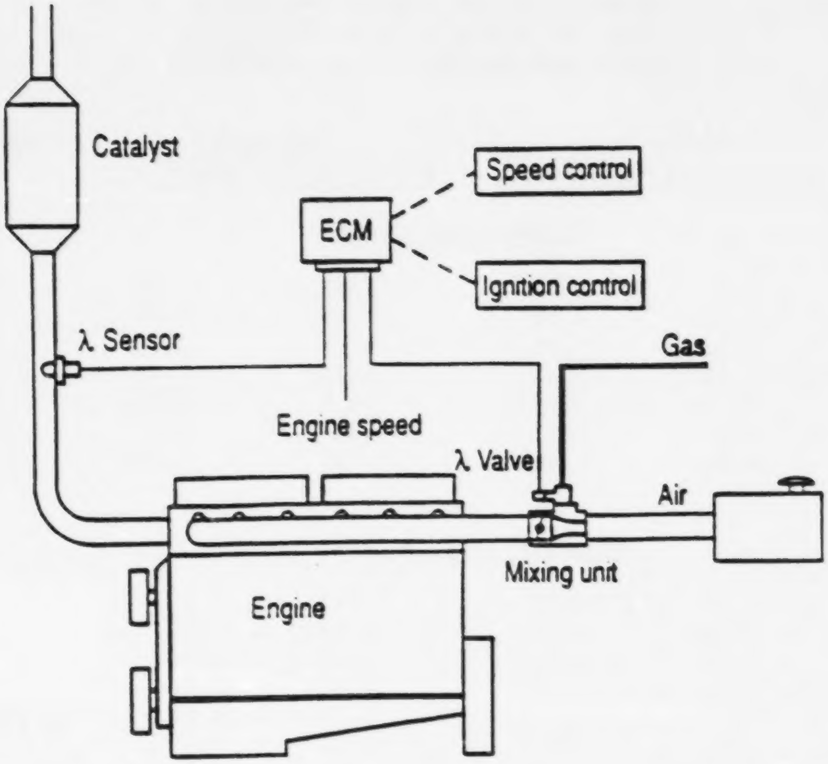
---

* The 0.10 standard applies to urban bus engines only. The 0.25 standard applies to all other heavy-duty diesel engines.

** The without catalyst results are hot start results only, not composite.

*** The less stringent standards apply to engines used in trucks greater than 14,000 lb. GVWR.

Figure 3-7


Catalyst
Speed control
ECM
Ignition control
λ Sensor
Gas
Engine speed
λ Valve
Air
Mixing unit
Engine

Closed Loop Electronically Controlled Air/Fuel System With Venturi-Type Mixer

Source: TNO Road-Vehicles Research Institute

The assumed emissions from current technology lean-burn and stoichiometric combustion engines are shown side by side in Table 3-4 and graphically for THC, CO and NOx in Figure 3-8. As can be seen, the HC emissions of the two engines are similar while the NOx and formaldehyde levels for the lean-burn engine are higher than the stoichiometric engine. It should be recognized that data on formaldehyde emissions from lean-burn CNG engines is very preliminary, with data available from only one engine test. The lean-burn engine particulate emissions are also higher than those from the stoichiometric engine, although both are very low. On the other hand, the stoichiometric engine has substantially higher CO emissions than the lean-burn engine. Finally, the stoichiometric engine has somewhat lower CO_2 emissions due primarily to a higher amount of the fuel carbon being emitted as CO (energy consumption from the two engines being nearly equivalent, as will be discussed below). A complete discussion of the environmental impacts of CNG emissions including a comparison with gasoline and diesel can be found in Chapter 5.

D. Engine Efficiency

The efficiency of CNG engines is an important discussion as it relates to both fuel economy and cost, as well as total CO_2 emissions and relative global warming effects. Fuel efficiency in particular is very important in the heavy truck market, especially among fleet and line-haul operators, as a large truck operator may spend as much as $10,000 annually for fuel alone.

A very large determinant of engine efficiency is the compression ratio, which is in a large part determined by the anti-knock quality (octane) of the fuel for a stoichiometric engine. For a diesel engine the compression ratio is high to initiate spontaneous (compression) ignition. Thus, a diesel engine has higher thermal efficiency than a stoichiometric gasoline engine. When deriving a CNG engine from a diesel engine, compression ratio must be reduced to control knock, reducing efficiency. Conversely, when using a gasoline engine base for a dedicated CNG engine, the compression ratio can be raised due to the superior knock characteristics of CNG, raising the thermal efficiency. Experiments with a single cylinder spark ignition engine showed an increase in thermal efficiency of 22 percent through both increased compression ratio optimization and a lean fuel mixture.[10] However, it is difficult to predict from this type of work exactly what efficency improvements can be made on a full size multi-cylinder engine.

The energy consumption rates for the various engines previously discussed are shown in Table 3-5. The current technology lean-burn CNG engine and the 1990 diesel L-10 values were estimated using a carbon balance procedure on the exhaust

Table 3-4

Current Technology Heavy-Duty CNG Lean-Burn and Stoichiometric Engine Emissions (g/BHP-hr)

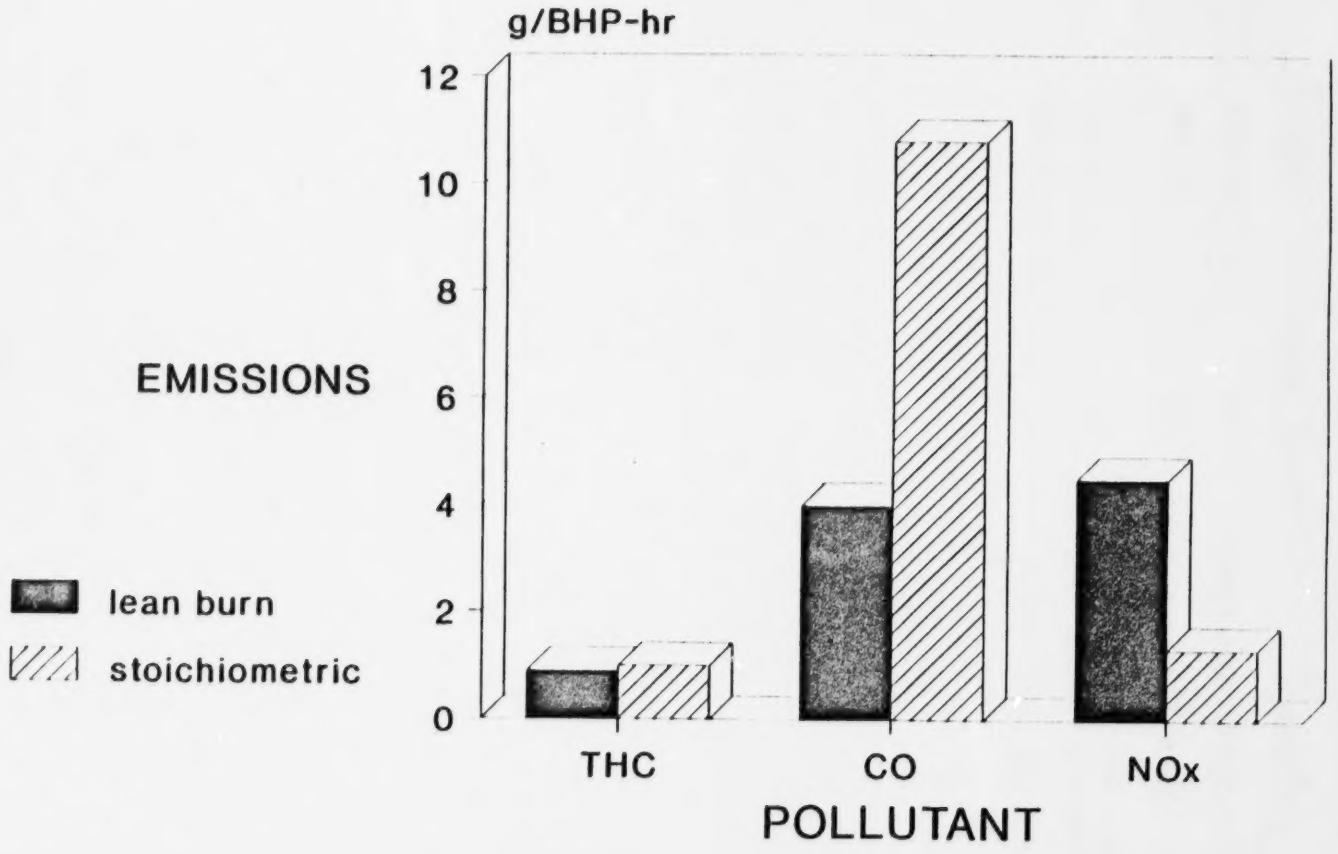
Pollutant	Lean Burn	Stoichiometric
THC	0.9	1.03
NMHC	0.09	0.15
NOx	4.5	1.33
Part.	0.06	0.01
CO	4.0	10.8
CO_2	575	557
Formaldehyde	0.05	0.0008

Table 3-5

Energy Consumption of Current Heavy-Duty CNG Engines (BTU/BHP-hr)

Engine	Diesel Fuel	CNG	Gasoline
L10/Current lean-burn	7180	10,000	--
Cat. 3406	7430	10,800	--
BUG (Chevy 454) diesel test cycle	--	9,950	--
Gasoline test cycle	--	8,950	10,036

FIGURE 3-8
COMPARISON OF CURRENT LEAN BURN AND STOICHIOMETRIC THC, CO AND NOx



components. The Caterpillar CNG 3406 is the steady state cogeneration engine while the diesel 3406 value is typical of a 1988 3406 engine.[8] The Chevrolet 454 gasoline value is also typical of a current engine.

As can be seen from Table 3-5 the lean-burn CNG engines consume 39 to 45 percent more energy than their diesel counterparts. This is not surprising given that the peak thermal efficiency of the diesel engines is higher than the CNG engines and the presence of throttling losses with the CNG engines at low loads. Conversely, as was expected, the BUG CNG engine consumes less energy than the Chevrolet 454 gasoline engine from which it was derived. In fact, an eleven percent reduction in energy consumption was achieved. Over the diesel test cycle, however, the CNG lean-burn and stoichiometric engines consumed almost the same amount of energy. As will be discussed in the section on optimized engine efficiency, optimized lean-burn CNG engines are expected to consume less energy than optimized stoichiometric CNG engines.

E. In-Use Performance

The in-use emissions performance and durability of CNG engines is an area where little information has been collected. Generally, in-use emissions deterioration would be a function of engine-out emissions deterioration and catalyst deterioration. Since the engine technology used on CNG engines is not fundamentally different in characteristics affecting likely durability than that currently being used on conventional engines, there is no reason to expect that, as CNG technology matures, the engine-out emissions deterioration of CNG engines would be significantly different than for gasoline or diesel engines. It is true that the BUG engine has experienced some difficulty maintaining proper calibrations during routine service, causing dramatic increases in HC and CO emissions.[11] Valve seat recession has also been a concern on some configurations. However, EPA expects such problems to be readily solvable on future versions.

As for in-use catalyst performance, it is again unlikely that, given the similarity of CNG catalyst technology to current in-use technology, there will be a significant difference in deterioration. Catalyst use on future diesel engines may present added durability issues due to the presence of particulate in diesel exhaust and the potential for catalyst plugging. However, the actual emissions impact of catalyst deterioration or of catalyst failure on a diesel engine would be much less than for the CNG engine, due to the fact that the emission reductions being provided by the diesel catalyst would only be relatively modest to begin with, in the range of 20 to

30 percent. A failed catalyst on a lean-burn CNG engine, on the other hand, would dramatically increase HC, CO and aldehyde emissions.

IV. Optimized Vehicle Projections

A. Emissions

Because the development of dedicated heavy-duty CNG technology is still in its early stages there is every reason to believe that significant improvements can be made in both emissions and efficiency. Past experience with gasoline and diesel technology would support this. The use of electronic controls, fast-burn combustion technology, increased compression ratios, and general engine optimization would seem likely candidates for improving CNG engines. Since, as noted earlier, dual-fuel engines offer limited opportunities for optimizing CNG combustion, the projections of optimized CNG engine emissions will be focused on dedicated engines. It should be noted that the projections derived here are based on limited current data and assumptions about projected improvements over current designs. Actual improvements made in optimizing CNG engines may yield different results than those projected here.

It appears that little of the work on CNG engine development thus far has been directed at emissions, as is evidenced by the lack of data. In this section projections of the potential emissions of optimized CNG heavy-duty engines of the mid-1990s will be made. It should be noted that no data on advance concepts for CNG were available and the projected improvements were based largely on assumptions about the potential of different technologies and extrapolation of gasoline and diesel vehicle experience.

Based on confidential prototype test data on the Cummins CNG L-10, as well as evaluations of the potential for improvements in engine-out emissions and catalyst efficiencies, the emissions of an optimized dedicated lean-burn CNG engine were projected. These projections are shown in Table 3-6 along with the current technology emissions. An improvement in fuel consumption was also projected, as will be discussed shortly. This improvement results primarily in CO_2 reductions, although its effects are felt on all emissions through engine-out reductions.

Given the relative infancy of CNG technology as compared to diesel technology and the limited amount of work which has been done on catalyst optimization for methane and other hydrocarbon components of CNG exhaust, significant reductions

Table 3-6

Estimates of Optimized Heavy-Duty CNG Lean-Burn Engine Emissions (g/BHP-hr)

Diesel Pollutant	Current Technology	1994 Diesel Standards	Projected Optimized
THC	0.9	1.3	0.6
NMHC	0.09	---	0.06
NOx	4.5	5.0	4.0
Part.	0.06	0.10	0.05
CO	4.0	15.5	1.5
CO_2	575	---	525
Formaldehyde	0.05	---	0.03

in future HC emissions should be possible. For this analysis a one-third reduction in total HC was projected through improved combustion and catalyst optimization. The percentage of non-methane HC was held unchanged at 10 percent of total HC as with the current technology numbers. A similar reduction in formaldehyde was projected.

Smaller percentage reductions in NOx and particulate were projected. In the case of NOx, there is little basis for improvement and, if anything, future efforts to improve engine efficiency and performance could put upward pressure on NOx. In the case of particulate, any reduction would likely come as a result of improved oil controls. Since 1991-type diesel engines such as that from which the lean-burn CNG engine was derived have already introduced many advanced oil control features, there is little improvement projected.

Finally, there are reasons to believe that future lean-burn CNG engines will have significantly lower CO. Although the current L-10 CNG engine is meeting a design target of 4.0 g/BHP-hr, there is evidence that CNG engines can reach CO levels much closer to current diesels (1.5-2.5 g/BHP-hr). This fact, along with the high CO conversion rate available from oxidation catalysts, should allow a significant reduction in future engine CO emissions.

Turning to stoichiometric combustion engines, engine-out emission and catalyst efficiency improvements were projected separately due to the availability of data on the current stoichiometric engine both with and without the catalyst. The current technology and projected optimized emission levels for stoichiometric heavy-duty CNG engines are shown in Figure 3-7. Considering first engine-out emissions, for all emission components except CO_2, which is largely a function of fuel consumption, it was assumed that levels could be reduced by 20 percent over current levels. This seems a reasonable assumption given the relatively young nature of dedicated heavy-duty CNG technology in comparison to the level of sophistication of gasoline engines. Such things as electronic controls, more precise fuel metering, and spark timing optimization offer means of improvement to current systems. Additionally, improved fuel efficiency, as will be discussed shortly, would also serve to reduce engine-out emissions.

For the stoichiometric three-way catalyst it was assumed that a five percentage point improvement could be made for all pollutant conversion efficiencies except particulate and gasoline test cycle NOx. No improvement in particulate was projected because future improvements in catalyst HC efficiency will likely not affect the heavy hydrocarbons which are characteristic of the particulate. Also, no improvement in NOx efficiency was projected for the gasoline test cycle catalyst. This is because the catalyst already showed a 91 percent efficiency and an efficiency much higher than this is not likely, at least in-use. The projected catalyst efficiencies for the future optimized stoichiometric engine are shown in Table 3-7, along with the resultant tailpipe emissions.

B. Future Optimized Engine Efficiency

The last topic of discussion for future optimized CNG engines is that of fuel efficiency improvements. there are a number of reasons to believe that fuel efficiency of dedicated CNG heavy-duty engines can improve over current technology. Natural gas as a fuel has a relatively slow flame speed compared to gasoline and diesel fuel. The development of fast burn combustion chambers would result in an increase in peak pressure and higher engine thermal efficiency. This is an area that can apply equally to lean-burn and stoichiometric engines.

For lean-burn engines, the current technology has a rather low compression ratio compared to the BUG engine and is a rather conservative design. Thus, an increase in compression ratio and a resultant increase in thermal efficiency could be expected. Also, the prechamber approach previously discussed has potential for higher cylinder pressures and better fuel economy. For these reasons it seems reasonable to assume that a significant improvement in fuel efficiency can be made for lean-burn engines. Thus, it was assumed that a ten percent decrease in brake-specific fuel consumption (from 10,000 to 9,000 BTU/BHP-hr) could be achieved in future optimized lean burn CNG engines over current technology. This is a significant improvement, but would still result in an energy consumption for the optimized lean-burn CNG engine about 25 percent higher than the diesel.

For stoichiometric engines, the compression ratio of the current technology CNG engine is already higher than that of the current lean-burn and there is not as much room for compression ratio increase. Also, the prechamber approach is not likely to be useful in stoichiometric engines, and no efficiency increase is expected here for it. For these reasons it is reasonable to assume that, while further improvement in stoichiometric CNG engine efficiency can be expected, it will not be as large as that for lean burn. Thus, it was assumed that only a five percent reduction in brake-specific energy consumption would be achieved on future stoichiometric CNG engines over current technology. This results in a fifteen percent lower fuel consumption rate for the optimized stoichiometric engine compared to the current Chevrolet 454

Table 3-7

Estimates of Optimized Heavy-duty CNG Stoichiometric Engine Emissions (g/BHP-hr)

	Current			Projected Optimized		
Pollutant	W/O Catalyst	Catalyst Efficiency	With Catalyst	W/O Catalyst	Catalyst Efficiency	With Catalyst
			Diesel Test Cycle			
THC	3.60	72%	1.00	2.88	77%	0.66
NMHC	0.82	82%	0.15	0.66	87%	0.09
NOx	6.62	80%	1.32	5.30	85%	0.79
Part.	0.01	0%	0.01	0.01	0%	0.01
CO	31.9	66%	10.8	25.5	71%	7.40
CO_2	529	---	557	499	---	534
Formaldehyde	0.03	97%	0.0008	0.02	97%	0.0006
			Gasoline Test Cycle			
THC	1.7	58%	0.72	1.36	63%	0.50
NMHC	0.40	78%	0.09	0.32	83%	0.05
NOx	5.75	91%	0.51	4.60	91%	0.41
Part.	0.01	0%	0.01	0.01	0%	0.01
CO	28.5	63%	10.6	22.8	68%	7.29
CO_2	474	---	500	453	---	480
Formaldehyde	0.02	99.5%	0.0001	0.02	99.5%	0.0001

gasoline engine. A similar comparison to other gasoline engines would be expected.

For an optimized stoichiometric combustion CNG engine operating over the diesel cycle test cycle this five percent reduction in energy consumption over current technology would result in a brake-specific energy consumption of about 9,450 BTU/Bhp-hr. Comparing this value to the optimized lean-burn combustion engine value of 9,000 BTU/Bhp-hr it can be seen that optimized lean-burn CNG engines are expected to be somewhat more fuel-efficient than their stoichiometric combustion counterparts.

V. Safety Issues for CNG Use in HD Applications

A. Introduction

For certain heavy-duty applications, CNG is likely to become a viable alternative in the near future. However, there are several issues which should be analyzed to insure that the relative safety risks of using compressed natural gas as a fuel for heavy-duty applications are known and addressed. These issues are discussed in these sections. The specific issues looked at include flammability, explosivity, toxicity, and special safety issues of concern to the use of CNG as well as the implications of these issues when using CNG as a fuel for heavy-duty vehicles. The other fuels looked at are gasoline and diesel fuel for comparison purposes.

For conventional fuels, there is a broad base of tabulated in-use experience and, as a result, detailed comparisons of many aspects of the safety issues can be made empirically. However, in the case of CNG used as a motor vehicle fuel, experience is only just now being built up and, therefore, there remains an insufficient supply of in-use data to produce meaningful statistical results.* Therefore, the safety analysis contained here will focus mainly on expert projections of the safety-related issues involved in the use of CNG as a heavy-duty motor vehicle fuel. This analysis is mainly qualitative in nature, although a limited amount of actual in-use data is included.

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* CNG fueled vehicles have been in use for as much as thirty years in other countries with no reports of unusual safety problems, however.

B. Fuel Properties and General Considerations

1. Toxicity

The issue of toxicity will receive only peripheral attention in this report. Natural gas, being mostly methane, is not toxic. However, because of its gaseous nature, it can act as an asphyxiant. Therefore, from a toxicity viewpoint, the only concern in handling methane is to ensure proper ventilation so that concentrations sufficient to cause asphyxiation do not form.

In contrast to CNG, diesel fuel and gasoline both pose significant toxicological risks. Gasoline and diesel fuel are toxic if ingested, inhaled, or even absorbed through the skin. The potential effects of acute or prolonged exposures are nausea, vomiting, cramping, liver and kidney damage, lung irritation, and central nervous system depression ranging from mild headaches to coma or even death.[12,13,14,15,16] In addition, both gasoline and diesel fuels have carcinogenic risks associated with them. While diesel fuel vapors are not known to be carcinogenic, skin tests show diesel fuel to be weakly to moderately carcinogenic. On the other hand, gasoline is believed to pose carcinogenic risks from vapors as well as from direct contact with the fuel.[17]

2. Flammability

With an estimated 15,000 to 20,000 fires resulting annually from motor vehicle accidents, the risk of fire is probably the greatest safety risk associated with fuels.[18] Associated with these fires are approximately 1700 deaths, 3700 serious injuries, 3600 moderate injuries and property damage costs of well over three billion dollars.[18,19] There are an additional 2553 reported service station fires annually resulting in approximately four deaths and 115 injuries.[18]

While all fuels are flammable, the conditions needed for ignition and the severity of the results of an ignition depend on the properties of the fuel. Table 3-8 summarizes the properties thought to be most important in assessing the hazards of different fuels as well as other key physicochemical properties.

Because of the varying properties of the different fuels, the probability of an actual ignition is strongly dependent on the conditions under which a fuel spill or leakage occurs. The analysis begins with a look at the hazards associated with a fuel escape under conditions with good ventilation (such as outdoors) and then reviews conditions with poor ventilation and the potential results should a fire occur.

Table 3-8

Selected Physicochemical Properties of Automotive Fuels

Property	CNG*	Gasoline	Diesel Fuel
Flammability limits, vol % in air	5.3 - 15.0	1.0 - 7.6	0.5 - 4.1
Detonability limits, vol % in air	6.3 - 13.5	1.1 - 3.3	---
Minimum ignition energy in air, mJ	0.29	0.24	0.3 (est)
Autoignition temperature, K(°F)	813 (1004)	501 - 744 (422-880)	533 (500)
Flash point, K(°F)	85 (-306)	230 (-45)	325 (125) min.
Flame temperature K(°F)	2148 (3898)	2470 (4478)	---
Energy content, lower heating value			
1. Btu/gal.	19,760 @ 2400 psi, 294k (70°F)	114,132 (AVG)	129,400 (AVG)
2. Btu/lb	21,300	18,900 (AVG) (60° api)	18,310 (AVg)
Diffusion coefficient in NTP air,*** cm/s	0.16	0.05	---
Buoyant velocity in NTP air,*** m/s	0.8 - 6	nonbuoyant	nonbuoyant
Density of liquid, g/cm^3	---	0.70 - 0.78 @ 1 atm	0.82 - 0.86
Density of gas relative to air = 1.00	0.555	3.4	>4.0 (est)
Liquid/gas expansion ratio	---	156	---
Vapor pressure or equivalent,**** atm	1	0.54 - 1.0 @ 311K (100°F)	0.0005 @ 311K (100°F)(calc.)
Viscosity of liquid @ NBP***, poise	---	0.002	0.02
Normal boiling point***, K(°F)	---	310 - 478 (100 - 400)	480 - 600 (405 - 620)
Threshold limiting value (TLV), ppm	asphyxiant	500	500
Storage conditions	Compressed Gas, 2400 - 3000 psig	Liquid @ ambient T&P	Liquid @ ambient T&P

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* Properties are primarily those of methane. It is recognized, however, that natural gas sources vary in composition. Property values will therefore deviate to a small extent from pure methane.

** Properties refer to Grade No. 2 diesel fuel.

*** NTP equals 293.15 K (68°F) and one atmosphere; NBP equals normal boiling point.

**** For gaseous fuels, refers to "equivalent vapor pressure" when released from high pressure storage container (see Sec. VII), or maximum possible pressure in ambient environment.

Source: "Gaseous Fuel Safety Assessment for Light-Duty Automotive Vehicles," M.C. Krupka, A.T. Peaslee, and H.L. Laquer, Las Alamos National Laboratory, November, 1983.

a. Ease of Ignition Under Conditions of Good Ventilation

Under conditions of good ventilation, accumulation of fuel vapor in flammable concentrations is likely only in close proximity to the vapor source. Any fuel release outdoors would likely be well-ventilated. Available studies also show that even fuel releases due to collisions in areas such as tunnels should be sufficiently ventilated to prevent the formation of hazardous concentrations of fuel vapor.[20] In these situations, the volatility of the liquid fuels combines with the lower flammability limits, vapor densities and diffusion coefficients of the vapors to form the most critical factors in assessing ignition probabilities. EPA's methanol safety analysis rated diesel fuel as the safest material under these conditions and gasoline as the most dangerous with methanol fuels being an intermediate risk.[13] These rankings follow the relative volatilities of the fuels. A study of the safety issues of CNG use done by the Los Alamos National Laboratory for DOE in 1983 concluded that CNG fuels were safer than gasoline due to the high rate of dispersion and the relatively higher lower flammability concentration.[21] Diesel fuel was once again considered to be the safest fuel due to the fact that it would take a relatively high temperature to allow an ignitable mixture of vapor to form (flash point 125°F).

b. Ease of Ignition Under Conditions of Poor Ventilation

Under conditions of poor ventilation, the probability of an ignition is greatly different than under conditions of good ventilation. Since the fuel vapors are confined to a closed space, the likelihood of ignition is greater for all types of fuels than under conditions where the vapors are allowed to disperse readily. These are the types of conditions which might be found in a storage or repair garage or in a poorly ventilated covered parking area.

Again, under these conditions, diesel fuel is the safest of the three alternatives due its very low volatility. Temperatures high enough to generate the needed vapor concentrations are rarely found unless an ignition source strong enough to heat the fuel is nearby. Therefore, diesel fuel under most conditions is relatively safe from a flammability standpoint.

Gasoline can easily form flammable or even explosive mixtures under poorly ventilated conditions since the vapors cannot disperse as readily. As with diesel fuels, vapors are heavier than air so that the greatest risk of fire or explosion would be near the ground. For this reason, existing repair and indoor refueling stations often put electrical equipment and other possible sources of ignition up in the ceiling.

CNG, as a lighter than air gaseous fuel also poses a serious flammability and explosion risk under conditions which do not allow the vapors to dissipate. These hazards would be similar to the types of hazards often faced by residential and commercial users of natural gas for heating or other uses. Furthermore, the most likely place for formation of flammable or explosive mixtures of natural gas would be near the ceiling. Therefore, facilities which would handle repairs or refueling of CNG vehicles indoors may not want to place ignition sources close to the ceiling. Proper ventilation and gas sensors would likely be utilized in any such facility to eliminate the possibility of a combustible mixture collecting. In some cases seperate facilities for CNG vehicles and liquid-fueled vehicles may be required.

3. Hazards Associated With a Fire

The most telling distinctions between liquid fuel fires and natural gas fires is the rate of combustion and the amount of smoke produced by combustion. Both conventional liquid fuel vapors and natural gas will rapidly combust any fuel vapors present in flammable concentrations once a source of ignition is introduced. The major differences in flammability characteristics are in sustained, severe fire properties. Pools of gasoline or diesel fuel burn with a defined rate of heat release based on the heat of combustion and the rate of combustion of the fuel and produce a large amount of smoke. Rather than burning from a pool at a fairly well defined rate natural gas will burn with a torch type flame at the site of the leak. The rate of heat release will be controlled by the rate of fuel release and various safeguards can be implemented to control the fuel release rate. These safety strategies are discussed in a later section. Furthermore, natural gas produces very little smoke while burning.

Diesel fuel fires tend to start slowly but progress violently. High heat release rates result in a high probability of spreading the fire to other nearby flammable materials or causing serious burns to exposed individuals.[13] Gasoline, due to its high volatility, immediately erupts into a fully developed fire. Because of the rapid burn rate, gasoline has an even higher heat release rate than diesel fuel and therefore poses an even greater risk for spreading the fire or for serious burns to individuals.[13] Also, both gasoline and diesel will produce a large amount of smoke during combustion. This smoke itself can pose serious risks of injuries to nearby individuals.

Natural gas, on the other hand, burns at a lower flame temperature than gasoline or diesel fuel. Since the rate of combustion would be defined by the rate of release of the fuel, it is more difficult to quantify a rate of heat release. It is, however, estimated by the Los Alamos report that the rate of heat release for CNG is less than that of burning pools of liquid fuel.[21] A more recent study by EBASCO indicates that the heat release rate would be less than 40 percent of the heat release rate of gasoline fires.[20] Furthermore the burning is more likely to be confined to a small area immediately surrounding the release point than for liquid fuel fires. Consequently the likelihood of spreading the fire is less for a CNG torch fire than for a liquid fuel pool fire. In turn, the likelihood of an individual receiving a serious burn would probably be less than for liquid fuel fires. Finally, since natural gas burns without producing sizeable quantities of smoke and toxic materials, toxic risks from exposure to the products of combustion would be less compared to gasoline and diesel fuel fires.

4. Issues of Special Concern in the Use of CNG

Several researchers have identified issues of special concern to CNG and pressurized gaseous fuels in general.[21,22] First of all, there is the inherent danger of storing and handling a compressed gas. If a fuel line should rupture, particularly at a refueling station, injury could result from the flailing hose. Another concern with compressed gases is the possibility of frostbite resulting from someone being exposed to gases cooled by rapid expansion or fixtures cooled by these gases. These issues are dealt with more thoroughly in section C below.

Second, there is the concern of the fuel cylinder being improperly restrained. Cylinders generally have greater structural integrity than the surrounding vehicle and therefore have the potential to penetrate into parts of the vehicles where they were not intended to be or to break loose from the vehicle and become a potentially dangerous projectile, especially in collisions. However, with proper placement and restraint of CNG cylinders, risks posed by fuel cylinders breaking loose should be no greater compared to conventional fuel tanks.

The Department of Transportation (DOT) has established standards for the safe transport of hazardous materials. Natural gas falls into this designation. These standards establish both maximum operating and burst pressure for cylinders, the type of testing required before use and periodically during the cylinder lifetime, and allowable contaminants in the compresed natural gas to prevent corrosion.[23] While the cylinders used on CNG vehicles in the U.S. meet these specifications, it should be noted that the specifications were designed for the transport of CNG and not specifically for the use of these cylinders as vehicle fuel tanks. DOT has not yet set standards for cylinders used in CNG vehicles.

There is also concern about these cylinders being able to withstand corrosion from external sources and from contaminants in the gas itself. Indeed, the National Fire Protection Agency has established purity standards for compressed natural gas which limit the water content to less than 0.5 pounds per million cubic feet, 0.1 grains of hydrogen sulfide per 100 cubic feet, and no more than three percent carbon dioxide for gas to be transported in steel cylinders. Pipeline quality gas specifications are generally less stringent. However, cylinders thus far have shown excellent resistance to corrosion from current gas supplies.

Furthermore, the cylinders must be able to withstand physical strain. Cylinders will be subjected to the strain of repeated cycles of pressurization and temperature swings. Rigorous standards have been set for structural resistance to such conditions and currently available CNG cylinders have routinely been certified to meet these standards.

Finally, there is the question of the integrity of the fuel cylinders and their ability to withstand physical abuse. Severe abuse tests have been performed on CNG cylinders to demonstrate their fundamental durability. These cylinders have survived being dropped in a car from a height of more than 60 feet, having sticks of dynamite strapped to the side of the cylinder and detonated, and being shot at with small caliber bullets.[24]

C. Implications for Vehicle Safety

1. Refueling

The hazards posed in refueling with compressed natural gas are different from those posed in refueling with conventional liquid fuels. As long as normal, properly functioning equipment is being used, CNG refueling should be generally less hazardous than refueling with gasoline or diesel fuel since there will be no toxic or flammable vapors escaping from CNG refueling equipment, as there often is with conventional refueling equipment. In the event of equipment failure, CNG systems would offer a significant advantage compared to gasoline or diesel systems in the area of environmental exposure. While gasoline and diesel fuel storage tank or dispensing equipment leaks could lead to contamination of the surrounding environment with toxics, CNG leaks would introduce no such toxic materials into the environment. On the other hand, CNG equipment failure could pose a greater risk of physical injury to the operator compared to gasoline and diesel fuel systems. These injuries could take the form of cryogenic burns from gas cooled by rapid expansion or injuries resulting from being struck by a flailing hose.[4] Both of these risks can be minimized by designing the equipment to both resist catastrophic failures and so that if such a failure were to occur, it would occur at a point which is already anchored, contains a valve to shut off the flow of fuel, and/or is in an area where people are not likely to be exposed to the leak.

In cases where the refueling is being done indoors, flammable concentrations of fuel vapors of any type can build-up. For CNG systems, very little vapor should be released during normal operation. However, in the event of fuel leakage from malfunctioning equipment, large quantities of vapor could rapidly escape. The risks of vapor build-up, however, can be minimized by enclosing the fuel line in a ventilation line. Since fuel leakage cannot be completely prevented, however, the best strategy for minimizing risks is building design. Proper ventilation and placement of equipment which could serve as ignition sources should greatly reduce the risks of fire or explosion posed by any fuel source.

2. Vehicle Operation and Crashes

During normal operation of existing fleets of CNG vehicles, it appears that small leaks have been observed with greater frequency than in conventionally fueled vehicles.[21] It would be reasonable to conclude that the highly-pressurized nature of the CNG fuel system could make it more prone to small leaks and to more fuel being released from a given leak. Small leaks pose concerns about vapors accumulating to flammable concentrations either in vehicle compartments or vehicle storage enclosures. Incorporation of design features such as vents in the vehicle body and ventilation of garages can mitigate the risks of fuel leakage. Currently, there is insufficient data to determine to what extent small fuel leaks actually pose any hazards.

In vehicle collision scenarios, CNG would appear to pose a level of risk somewhere between diesel fuel and gasoline. To analyze collision hazards it is necessary to evaluate the risks of, and the likely extent of, fuel leaks. It is also necessary to examine the ease with which such problems can be dealt with in the event of combustion of leaked or leaking fuel.

In the absence of extensive data on the use of CNG vehicles, it is difficult to make an accurate assessment of the relative risks of fuel release. However, some assessments can be made as to estimates of relative risks. Because of the structural integrity needed by the fuel storage cylinders to hold compressed natural gas, these cylinders are much more likely than gasoline or diesel fuel tanks to survive collisions without release of fuel from the storage tank. On the other hand, fuel lines, valves and fittings would be more prone to severe leaks than gasoline or diesel systems because of the pressurized nature of the fuel. However, safety devices such as fuel release regulators and solenoid valves to shut off fuel flow when the engine stops can be built onto the fuel cylinder to lessen the severity of any release of natural gas from a CNG vehicle, and minimize the significance of this risk.

In the event of a fuel release resulting in a fire, the resulting problems from a CNG fire are likely to be easier to deal with. First of all, fires from liquid fuels are difficult to extinguish and difficult to control if they are not extinguished. On the other hand, natural gas torch fires (which are the only kind likely to be sustained) can be extinguished by shutting off the fuel source, which is not generally possible in liquid fuel fires. Some currently in-use CNG vehicles have a readily accessible quarter turn shut-off valve for this purpose. Should it be difficult to shut off the flow of CNG, it should still be possible to control the damage from the fire because of its localized nature. Severe explosions are unlikely in any case since CNG cylinders are designed to handle conditions likely to lead to explosions and will eventually vent off gas which will burn in a relatively controlled manner rather than rupturing to produce an explosive release.

Despite the lack of a database of CNG use sufficient to draw definitive conclusions, there are some surveys and studies which do present some in-use information. In 1987, the American Gas Association completed a survey of fleet use of dual-fueled vehicles. Their survey, covering 434.1 million miles of accumulated use with dual-fueled CNG/gasoline vehicles, claimed that the injury rate for CNG vehicles was significantly less than for all U.S. vehicles and fewer fires were attributed to the CNG fuel system than to the gasoline fuel system.[24] Furthermore, data from New Zealand indicated that CNG vehicles caught fire much less frequently than did conventionally fueled vehicles.[20] However, the information about vehicle operation characteristics in these reports lacked information on number of miles travelled on CNG and on injury causes was therefore insufficient to enable any solid conclusions to be drawn from the data reported.

In cases where the fuel release occurs before a source of ignition is available, both gasoline and CNG have the potential to form a flammable cloud of vapor which could burn explosively when an ignition source is introduced. However, such conditions are only likely under conditions of poor ventilation. Tunnels and lower decks of multi-decked bridges have attracted attention as a possible location where explosive conditions might occur following an accident. Both the Triborough Bridge and Tunnel Authority and the Port Authority of New York and New Jersey, as part of their general restrictions on compressed gas transportation (stemming from a severe LP-gas accident in the first half of this century in the Holland Tunnel), limit the amount of compressed natural gas which can be transported in these areas to less than 100 pounds of gross weight with each cylinder being less than ten pounds of gross weight. This same restriction applies to all flammable compressed gases.[25,26]

In spite of these concerns, available studies suggest that tunnels generally have sufficient ventilation to prevent gas vapors from building up large volumes of flammable concentrations, so that the relative flammability risks of the fuels should be similar to those for conditions of good ventilation.[21] Both the Los Alamos report and the recently completed EBASCO report for the New York State Energy Research and Development Authority, Brooklyn Union Gas Company and Consolidated Edison Company on the safety of CNG in tunnels concluded that CNG is safer than gasoline for use as a transportation fuel in tunnels, although neither study claimed CNG would be safer than diesel for use in these environments.[20,21] The EBASCO report in particular did a detailed modeling study of likely fuel concentrations in the Holland tunnel which would result from a rapid release of fuel from a bus and concluded that there would be only a very limited time and location where there would be a flammable concentration of natural gas, and that the only scenario under which natural gas vehicles might pose a greater risk than gasoline vehicles would be if the fuel line ruptured under the vehicle and the natural gas became trapped under the vehicle with no safety devices to stop the flow of gas or to ventilate the undercarriage of the bus.

3. Maintenance

The issue of maintenance might also pose some concerns. On CNG equipped vehicles, it is possible that a maintenance worker could release a large amount of fuel by inadvertently creating a vent in the fuel system. In such a case, the worker could also face the risk of a cryogenic burn as described earlier. If the fuel release occurred outdoors, no other hazards should be posed unless there was an ignition source immediately present, due to the rapid dispersion of the gas. On the other hand, if the maintenance were being performed indoors, there is a potential for the rapid formation of a flammable or explosive cloud.

The same suggestions for garage design described earlier would reduce the hazards associated with a fuel leak during maintenance. In particular, well ventilated buildings will greatly reduce the risks of a flammable or explosive cloud forming. Furthermore, it should be pointed out that a vehicle with a properly functioning solenoid valve to shut off the fuel flow when the engine is not running could minimize the possibility of the maintenance crew accidentally releasing a large volume of fuel. With the establishment of proper maintenance procedures (such as shutting the fuel flow valve during maintenance) and the accumulation of experience in maintaining CNG vehicles, the risks associated with maintaining CNG vehicles should not necessarily be different than for maintaining conventionally fueled vehicles.

D. Summary

Evaluating CNG as an alternative fuel for use in heavy-duty vehicles from a safety standpoint, it can be seen that CNG poses some unique safety concerns due to its gaseous and pressurized properties. On the other hand, it has some properties which are superior (from a safety viewpoint) to those of conventional liquid fuels, including the fact that the material itself is not toxic (a significant safety benefit over conventional liquid fuels). Owing to the lack of extensive experience with this fuel in the United States, it is difficult to draw definitive conclusions regarding the safety of this fuel relative to fuels with a broader base of use. However, it would appear that the area of most concern and uncertainty would be flammability. Studies have suggested that CNG would be safer than gasoline in well ventilated areas but could pose a greater risk of explosion in areas with poor ventilation. In the event of a fuel leak or spill, therefore, the risk of fire from CNG could be comparable to the risk from gasoline and somewhat greater than the risk from diesel fuel. However, the consequences of a CNG fire should be less severe than for gasoline or diesel fuel fires. Although the relative likelihood of fuel spills or leaks from CNG as compared to conventional fuels is yet to be determined, it would appear that CNG would not pose a greater flammability risk than gasoline. Despite the need for further work in ensuring that fuel leaks are minimized and controlled, in developing safe maintenance practices and in assuring that refueling can be done safely, it would appear that there are no safety issues which cannot be dealt with which would preclude the development of CNG as an alternative fuel for heavy-duty vehicles. Taking all factors into consideration, it would appear that CNG is certainly no more dangerous than gasoline as a vehicle fuel.

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CHAPTER 4

ECONOMICS OF USING CNG IN HEAVY-DUTY APPLICATIONS

I. Introduction

In this chapter the economics of using CNG as a heavy-duty vehicle fuel will be presented. First, the domestic natural gas supply will be discussed followed by a presentation of natural gas prices. Next, CNG refueling station costs and hardware will be discussed. Following this, overall fuel costs for current and future natural gas, gasoline and diesel fueled heavy-duty vehicles will be compared. Finally, vehicle and engine costs associated with dedicated CNG use will be discussed.

II. Domestic Natural Gas Supply and Price

The total United States proved reserves of dry natural gas in 1987 were 187.2 trillion cubic feet (TCF).[1] At current domestic usage rates this is enough to supply the United States for over nine years.[2] These proved reserves only include identified sources whose quantity, quality and location are known and which can be economically extracted with existing technology. Addition of estimates of conventional resources which have been identified and are estimated to be potentially recoverable economically bring the total U.S. conventional resource base total to about 900 TCF.[3] Large amounts of natural gas from unconventional resources such as coal seams, Devonian shale, geopressurized brines and tight gas reservoirs are also available but would only be economical to extract at somewhat higher, though unclear, increases in natural gas prices.[4] For the purposes of this report it will be assumed that the use of CNG as a heavy-duty vehicle fuel will not impact the domestic demand or price of natural gas to any significant degree. This is a reasonable assumption given that a significant penetration of CNG into the total domestic heavy-duty fleet (i.e., ten percent) would result in an increase of natural gas use of just two to three percent, still well below total domestic usage rates of the early 1980s.

The United States currently has a massive natural gas transmission and distribution pipeline network in place which serves a large portion of the country. Also, in most major cities and many other areas there is an extensive distribution network in place which can be easily tapped. For the purposes of this study it will be assumed that CNG would generally be used for heavy-duty vehicles in areas which already have a distribution infrastructure in place and thus, no new capacity would need to be installed. Also, it is likely that heavy-duty CNG applications would generally be centrally fueled fleets in urbanized areas and would have ready access to natural gas distribution lines.

The American Gas Association has recently published projected natural gas prices for vehicle refueling stations to the year 2005.[5] These projections for 1995 (in 1989 dollars) range from \$2.59/mmBTU to \$5.89/mmBTU (lower heating value) depending on the region of the country being considered. This range of prices will be used in this report to develop natural gas vehicle fuel cost estimates.

No attempt will be made in this report to predict future natural gas price trends. Unlike some other alternative fuels such as methanol, where a whole new market must be developed, the use of natural gas as a heavy-duty vehicle fuel is expected to result in little perturbation in the natural gas market. Thus, future predictions of price trends are not as critical here as in the analysis of other alternative fuels.

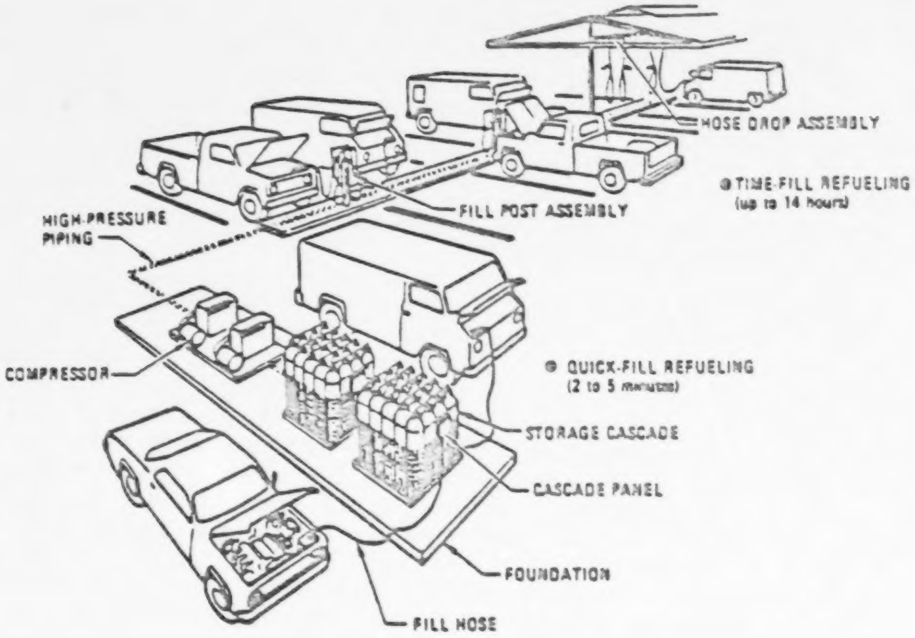
III. CNG Refueling Station Cost

In this section the cost of CNG refueling stations for heavy-duty applications will be examined. First, a description of CNG refueling station operation, hardware and some factors influencing station design will be presented. Next, some typical current prices for different refueling station components will be shown. Finally, the range of total station costs will be discussed. Due to the wide variety of heavy-duty vehicle fleet sizes and applications, the purpose of this section is to give the reader some idea of the range of costs involved in a CNG refueling station rather than to define and cost out a "model station" to represent the "typical" heavy-duty station.

A. CNG Refueling Station Hardware

In contrast to liquid fuels, CNG is a gas and must be compressed for storage onboard a vehicle. Thus, the refueling station equipment needed for CNG is different than that for gasoline or diesel fuel. Generally, there are two methods of refueling a CNG vehicle, slow-fill and fast-fill. Although these two methods are similar in some respects, they are quite different in others. A diagram of a typical CNG fueling station utilizing both fill methods is shown in Figure 4-1.

Figure 4-1


HOSE DROP ASSEMBLY
TIME-FILL REFUELING
(up to 14 hours)
HIGH-PRESSURE PIPING
FILL POST ASSEMBLY
COMPRESSOR
QUICK-FILL REFUELING
(2 to 5 minutes)
STORAGE CASCADE
CASCADE PANEL
FOUNDATION
FILL HOSE

Typical CNG Refueling Station

Source: "Assessment of Methane-Related Fuels for Automotive Fleet Vehicles", DOE/CE/50179-1, February 1982.

With the slow-fill method there is a direct connection between the vehicle and the natural gas compressor. Thus, refueling time is directly related to the total fuel capacity of the vehicle or vehicles being fueled and the discharge rate of the compressor, which is generally given in standard cubic per minute (SCFM). Slow-fill can take less than one half hour for a single vehicle fueled on a larger compressor, as is the case, for example, with the Brooklyn Union Gas (BUG) buses discussed in Chapter 3.[6] However, slow-fill stations generally refuel more than one vehicle at a time and often use smaller compressors than the BUG program station. Thus, a typical slow-fill operation will generally take several hours and is usually performed overnight.

In contrast to slow-fill, fast-fill systems utilize a large-volume compressed gas storage system, or "cascade", between the compressor and the vehicle. Generally, the cascade is divided into three banks of cylinders, with each bank at a different pressure. The lowest pressure bank is used first and an automatic or manual sequential valve system switches to the higher pressure banks as the pressure between the cascade and the fuel tank is equalized. Through the successive connection with higher pressure banks the vehicle can be refueled in a matter of several minutes with fast-fill, as opposed to several hours with slow-fill. Similarly to fast-fill vehicle fueling, the fast-fill cascade banks are filled selectively by the compressor through a priority valving system, usually with the highest pressure bank being filled first.

Station design including choice of slow-fill versus fast-fill, compressor sizing, cascade sizing (if fast-fill), and the number of fuel hoses is determined by the number of vehicles to be fueled, their onboard fuel storage capacity, and their demand pattern. A small captive fleet may only require a small compressor and slow-fill capability to refuel all vehicles together overnight. A larger fleet will require a larger compressor, more fuel hoses and may even utilize some fast-fill capabilities. With this system vehicles could generally be slow-filled together overnight, but fast-fill would be available for special-purpose filling during the day. Finally, a commercial fueling station such as a truck stop would be exclusively fast-fill and would have a very large compressor and cascade capacity, as well as fuel dispensers with metering capability rather than simple fuel hoses.

Natural gas compressors are generally two to four stage compressors with a discharge pressure of 3,600 psig. Compressors for small installations such as fleet stations generally have a discharge rate of well below 100 SCFM. The gas supply for the compressor is taken from an underground natural gas transmission line, much like a residential home hook-up. The natural gas pressure in these lines is generally one to five psig for distribution lines, although main transmission lines can have pressures of several hundred psig. The line pressure to the compressor affects cost and sizing as less compression is needed when starting with a higher gas inlet pressure.

In addition to the refueling hardware itself there are other components to the CNG refueling station. These include a concrete pad to mount the compressor on, as well as any enclosure that may be used to protect the compressor and cascades (if any) from the elements. There may also be a significant piping link to the gas source depending on the proximity of the station to the underground gas line. However, for most applications in any sizeable city this would likely be a fairly short line.

B. CNG Refueling Station Hardware Cost

In order to understand the total cost of a CNG refueling station it is useful to first look briefly at typical costs of the various components of a station. At the heart of any refueling station is the compressor. This is usually the single most expensive component of the station. The cost of a variety of compressors from various sources was compiled and is presented in Table 4-1. As can be seen there is a fairly linear relationship between the compressor cost and its capacity. Generally, a small fleet would use a compressor on the lower end of the capacity scale while a larger fleet would likely need a compressor on the higher end of this scale. A high volume commercial truck stop would likely require a compressor sized larger than anything on this table.

Table 4-2 shows typical costs for other CNG refueling station components. The fueling post for slow-fill or fast-fill application would typically cost $500 to $1,000 per hose (vehicle). In contrast, a two hose dispenser for commercial fast-fill use, which may include metering capabilities and a sequential valve system, can cost over $35,000.

If fast-fill capability is desired, a small cascade and associated priority and sequential valving will cost under $15,000. This type of cascade system would generally be used to fast-fill only a few trucks during the day. If the fleet were large or utilized fast-fill exclusively, several small cascades or one or more large cascades may be required.

Table 4-1

Typical CNG Refueling Station Compressor Costs

Source	Capacity (SCFM)	Inlet Pressure (psig)	Cost
A	4.5	0-5	$ 12,800
B	25	--	30,000
A	30	0-5	37,000
C	30	5-15	39,500
B	30	--	40,000
B	50	--	46,000
A	57.8	0-5	50,000
C	63-85	40-60	41,500
C	100	150	45,000
A	130	0-5	86,000
D	130	15	126,000
A	155	0-5	90,000

Sources: References 6 through 9.

Table 4-2

CNG Refueling Station Component Costs

Component	Cost
Fuel Post	$500-1,000/Vehicle
Dispenser (2 nozzle)	25,000-35,000
Cascade (20 cylinder-9,200 SCF)	8,500-9,800
Cascade (3 20" x 22' tubes, 27,000 SCF)	35,000
Sequential & priority valve systems	2,600-5,000(for both)

Sources: References 6 through 8.

C. Total CNG Refueling Station Cost

The total cost of a CNG refueling station is obviously dependent a great deal on its total capacity and whether or not it is a fast-fill system. To give some idea of the price range of CNG refueling stations, Table 4-3 shows estimates for the total cost of a small light-duty fleet station and a large truck stop, as well as the actual costs of the refueling station for the BUG bus program in Brooklyn, NY, and a refueling station used for a small (10 vehicle) school bus fleet in Syracuse, NY. The small fleet station estimate shows that it is possible for a small fleet (17-35 light-duty vehicles, significantly fewer for heavy-duty) to utilize a slow-fill refueling station which costs well under $100,000.[10] Conversely, a commercial truck stop which would require a large compressor and cascade capacity, as well as meter-type fuel dispensers is projected to cost well over $600,000.[11] Although this report is intended to cover issues specific to CNG use in heavy-duty applications, it is reasonable to assume that the lightest of heavy-duty CNG vehicles (pick-up and delivery vans, for example) may refuel at public stations intended primarily for light-duty applications. Cost estimates for these types of stations were developed in Volume I of this report and are shown to be $225,000 to $396,000.

Table 4-4 shows the cost breakdown of the CNG refueling station used for the school bus fleet in Syracuse, New York.[12] This station utilized two 30 SCFM compressors for a total capacity of 60 SCFM. It also had a small cascade for fast-fill purposes. Although this station was only used for ten buses its capacity would allow a fleet significantly larger than this, as the compressors were only required to run about five hours a day. This station is an excellent example of the type of station a small captive fleet could use.

From the perspective of a somewhat larger station, Table 4-5 shows the cost breakdown of the BUG bus refueling station. This station is a simple slow-fill system with a 130 SCFM compressor and a single two-hose metered-type dispenser. The total cost for this system is rather high for the initial application (two buses) for a couple of reasons. First, the compressor is a very large one for a slow-fill system servicing a two vehicle fleet. However, this allows slow-filling of a single bus in less than thirty minutes. In fact, when the compressor is operating 20 hours a day this system is capable or refueling 45 buses in a day. Second, Brooklyn Union Gas is authorized to sell CNG from this station commercially, thus the expensive dispenser rather than an inexpensive fill post. This fact would also justify the large compressor capacity. Finally, the installation and materials cost is somewhat high as the original concrete slab and support pilings were placed, unbeknownst to the designers, on an abandoned landfill with poor soil conditions. Thus, following initial startup the system had to be disconnected so that a new concrete slab and additional support could be added, adding three weeks to the initial five-week installation time.

Table 4-3

Total Costs for Heavy-Duty CNG Refueling Stations

Station	Cost
Small fleet station	$ 81,500
Syracuse school bus station	101,933
BUG bus station	278,108
Commercial truck stop	641,000

Sources: References, 6,10,11,12.

Table 4-4

Cost Breakdown for Syracuse Bus Refueling Station

Equipment (incl. two 30 SCFM compressors)	$ 78,133
Compressor pad	3,500
Installation	1,000
Total (1982 dollars)	$ 82,633
Total (Current dollars)	$101,933

Source: "Dual-Fuel School Bus Demonstration", New York State Energy Research and Development Authority, Albany, NY, October 1986.

Table 4-5

Cost Breakdown for BUG Refueling Station

Compressor (130 SCFM)	$126,286
Dispenser (two hose)	25,000
Other Materials	9,653
Installation	117,169
Total	$278,108

Source: C. Spielberg, "Compressed Natural Gas Program Monthly Report #2, January-May 1989," New York City Department of Transportation, September 12, 1989.

With this perspective on the BUG station, it appears that a slow-fill system designed for overnight fill of several vehicles could be substantially cheaper. Use of a smaller compressor and simple fill posts rather than a meter-type dispenser, together with the elimination of the unexpected soil condition problem, could easily cut the cost of this system in half. A larger compressor and the addition of some fast-fill capacity (at $15-20,000 total additional cost for cascade, priority and sequencing valves, additional fueling hoses, etc.) would still likely keep total system cost under $200,000. Thus, for the purposes of a small to moderate sized fleet the total refueling station cost could range from $80-200,000 depending on total capacity and whether or not fast-fill capacity is included. Conversely, the worst case would likely be the large fast-fill truck stop at over $600,000.[11] However, for the purpose of this report it will be assumed that most heavy-duty CNG applications will utilize a smaller station in a fleet setting.

It should be noted that the cost of land is not included in this discussion as part of the total CNG refueling station cost. For the purposes of this report it is assumed that a fleet CNG refueling station would be constructed on the site of the fleet's current refueling station and no additional land costs would be incurred. However, EPA recognizes that, due to the physical size of the the compressor and cascades, placing a CNG refueling station within the physical confines of an area designed for a diesel or gasoline refueling station may present a problem at some facilities, resulting in some added cost.

Finally, in the case of truck stops, which are generally located away from urban areas, there may be a cost associated with the pipeline required to connect the station to the natural gas distribution pipeline. This connection was estimated by the Department of Energy to average between 1 and 5 miles long depending on the area of the country, and was estimated to cost $200,000/mile.[11] However, for the purposes of this report it was assumed the most heavy-duty applications of CNG, at least in the near term, would be in centrally fueled fleet settings in urban areas, which would not incur this cost. Thus, it was not included in the economic analysis contained in this chapter.

IV. Heavy-Duty CNG, Gasoline and Diesel Vehicle Fuel Cost

This section will present an estimate of the relative fuel costs for both current and future CNG, gasoline and diesel fueled heavy-duty vehicles. First, an "equivalent gallon" of natural gas in relation to gasoline and diesel fuel will be established so the fuel costs can be projected on an energy basis for direct comparison. Second, the cost of compressing the natural gas for refueling will be calculated. The capitalized refueling station cost will then be calculated and all of the factors will be combined for a comparison of per equivalent gallon fuel costs. Finally, the total vehicle fuel costs for both current and future CNG, gasoline and diesel fueled heavy-duty vehicles will be estimated using these fuel prices, and factoring in relative engine efficiencies and other relevant factors.

A. Basis of Comparison

Although natural gas is stored and burned in a gaseous form, it is easiest to compare natural gas consumption to consumption of gasoline or diesel fuel on an energy basis (i.e., "equivalent gallon"). The energy density of natural gas is typically 1,030 BTU/SCF higher heating value (HHV).[13] However, for purposes of comparison with gasoline and diesel fuel, the lower heating value (LHV) of natural gas must be used. This value is not usually quoted, but an earlier EPA technical report determined that the LHV of natural gas is typically around 90 percent of the HHV.[14] Thus, an energy density of 930 BTU/SCF will be used for natural gas in this report. Comparing this to the BTU/gal value for diesel fuel from Table 3-1 and 114,132 BTU/gal for 9 RVP gasoline[13] yields an energy equivalence of 122.7 SCF of natural gas to one gallon of gasoline, and 139.6 SCF of natural gas to one gallon of diesel fuel. These relationships will be used for the comparison of relative fuel costs between the fuels.

B. Compression and Station Maintenance Costs

The natural gas prices just presented are not the only factor in the cost of natural gas to the heavy-duty CNG vehicle operator. As will be seen, there is a cost of energy to compress the natural gas during refueling, which is dependent on the efficiency of the compressor and the price of energy to power the compressor motor. Also, station maintenance costs are significant enough to consider. These costs must be factored into the cost of natural gas as a vehicle fuel.

Data on the energy used per volume of natural gas compressed are available for four different compressors in both public and fleet use in Canada.[15] These compressors varied in output delivery capacity from 20 to 178 SCFM. The energy used to power the compressors ranged from 0.0075 to 0.0099 KW-hr/SCF, depending on compressor efficiency.

Compressors currently used in CNG refueling stations are generally powered by electric motors. It is reasonable to assume that in the future compressors may be powered by natural gas engines at a significant energy cost savings over electricity. This is especially likely in the case of large, commercial station compressors. However, since current compressors generally use electricity and most heavy-duty applications of CNG are expected to utilize smaller compressors, electricity costs will be used here to calculate compression costs while recognizing that these costs may be significantly reduced in some future cases.

The 1988 national average commercial price for electricity was 7.01¢/KW-hr.[13] Using the equivalent gallon relationships previously derived along with this current electricity price yields current natural gas compression costs of 6.4-9.0 cents per equivalent gallon of gasoline, and 7.3-9.7 cents per equivalent gallon of diesel fuel.

Based on actual maintenance cost data from a variety of actual CNG refueling stations, DeLuchi et.al. estimated CNG station operation and maintenance costs to be $0.25-0.50/mmBtu.[16] Using the energy equivalences established earlier results in CNG station operation and maintenance costs of $0.03-0.06 per equivalent gallon for both gasoline and diesel fuel.

C. Capitalized Service Station Cost

In order to include the capitalized refueling station cost in the cost of natural gas a typical refueling station configuration was assumed. In general, station cost and station capacity are somewhat linear [17], and the capitalized refueling station cost is probably much more dependent on the utilization rate of the station than on it's capacity. For example, an urban transit bus fleet would have a fairly low utilization rate as it's vehicles would be on the road all day and could only be refueled at night. In contrast to this, a fleet of delivery vehicles which are in and out of the facility throughout the day could much more effectively utilize some fast-fill capacity during the day in addition to refueling at night. Thus, for the purposes of this report a single station design will be used and capitalized refueling station costs will be derived using high and low utilization rate scenarios.

The refueling station chosen is similar to the one previously discussed for the Syracuse school district. This station has two cascade banks for fast-fill capability and 60 SCFM compressor capacity. Further, this station is assumed to cost about $100,000. The per-equivalent-gallon costs will be calculated based on a 10 year payback period with a 10 percent rate of return.

For the low utilization rate scenario it was assumed that the vehicles would only be available for refueling 8 hours a day. In addition to operating the compressor for 8 hours in slow-fill operation, the cascades could be used initially to fast-fill additional vehicles during this 8 hour period, utilizing the compressor an additional 4 hours a day for cascade filling. This means that this station could refuel about 11 urban transit buses, each using the equivalent of 27 gallons of diesel fuel a day (similar to the BUG buses). This scenario yields capitalized refueling station costs of 12.8¢/gal for gasoline and 14.6¢/gal for diesel fuel.

For the high utilization scenario is was assumed that the compressor could be operated 20 hours a day, making efficient use of both slow- and fast-fill capacity. Although this scenario is probably not representative of an urban transit operation, for purposes of comparison to the low utilization scenario this type of operation could refuel around 20 urban transit buses daily. This high utilization scenario yields capitalized refueling station costs of 7.5¢/gal for gasoline and 8.2¢/gal for diesel fuel.

D. Relative Fuel Prices

Tables 4-6 and 4-7 shows the relative comparison of fuel prices between gasoline and CNG, and diesel fuel and CNG, respectively. The gasoline prices were taken from a previous EPA report.[18] The diesel cost is the average of the first seven months of 1989, without taxes.[13] Although state taxes for gasoline and diesel fuel are similar, Federal taxes for diesel fuel are six cents/gallon higher than for gasoline. In both cases, however, the same gasoline tax was assumed to be applied to CNG on an energy-equivalent basis. This was done because it is likely that a single taxation strategy would be used for CNG, and given the potential for light-duty applications, equivalent gasoline taxes seem most probable. The tax on a diesel-equivalent gallon of CNG is somewhat higher than for a gasoline-equivalent gallon of gasoline, due to diesel fuel's higher energy density.

E. Relative Vehicle Fuel Costs

The total vehicle fuel cost comparison between CNG and gasoline or diesel fuel must take into consideration not only relative engine energy use, but also the fuel economy effects of increased fuel storage weight and, as was just discussed, the cost of natural gas compression. As was discussed in Chapter 3, a current stoichiometric CNG engine uses almost 11 percent less energy than its gasoline counterpart, while the future optimized CNG engine uses some fifteen percent less

Table 4-6

Gasoline and CNG Energy Equivalent Price Comparison

Cost Classification	Gasoline	Natural Gas
Extraction, refining, other	$0.69	--
Long-range and local distribution	0.06	--
Current natural gas end user delivered price range*	--	$0.30-0.67
Service station markup**	0.09	--
Capitalized refueling station cost	--	$0.08-0.13
Compression cost	--	$0.06-0.09
Operation and maintenance cost	--	$0.03-0.06
Profit markup***	--	$0.00-0.01
Taxes	0.24	0.24
Total	$ 1.08	$0.71-1.20

---

* The end user price range for natural gas includes all distribution costs

** The service station markup for gasoline includes all overhead and operating costs as well as profit markup

*** The $0.00 profit markup applies to fleet-owned stations while a profit of $0.01 was assumed for commercial stations

Table 4-7

Diesel Fuel and CNG Energy Equivalent Price Comparison

Cost Classification	Diesel Fuel	Natural Gas
End user diesel fuel price*	$0.56	--
Current natural gas end user delivered price range	--	$0.34-0.76
Service station markup**	$0.09	--
Capitalized refueling station cost	--	$0.08-0.15
Compression cost	--	$0.07-0.10
Operation and maintenance cost	--	$0.03-0.06
Profit markup***	--	$0.00-0.01
Taxes	0.30	0.27
Total	$ 0.95	$0.79-1.35

---

* The end user diesel fuel price is the price charged to fleet operators rather than for resale (i.e., to commercial retail outlets)

** The service station markup for diesel fuel includes all overhead and operating costs as well as profit markup

*** The $0.00 profit markup applies to fleet-owned stations while a profit of $0.01 was assumed for commercial stations energy. Conversely, a current technology lean-burn engine uses 39 percent more energy than its diesel counterpart, while the future optimized lean-burn CNG engine is assumed to use 25 percent more energy.

Fuel storage weight is an important part of the total vehicle fuel cost as it affects total vehicle weight and, thus, fuel economy. For the purpose of this study it will be assumed that the vehicles being compared will have equivalent range (i.e., equivalent fuel capacity). This assumption is being made in order to allow a direct comparison between the fuel types. This may be somewhat of a worst case approach, as many heavy-duty vehicles could likely operate satisfactorily with less fuel storage capacity than they currently have. However, as will be described below, the overall impact on fuel consumption of maintaining equivalent range is small.

For the purpose of calculated fuel storage weight and fuel economy penalties two model vehicles were chosen which represent excellent candidates for dedicated CNG use in a captive fleet setting. The first is a UPS parcel delivery truck similar to the ones discussed in Chapter 3, with the exception that this vehicle will be assumed to be a dedicated CNG vehicle and will not have the 30 gallon gasoline tank and fuel weights included in the weight calculation. The second is an urban transit bus with the CNG fuel storage equivalent of a 100 gallon diesel fuel tank. The actual weight calculations and resultant fuel economy penalties are derived in Chapter 5. However, the results of these calculations show that bringing the UPS delivery truck to the equivalent range on CNG as it would have as a gasoline vehicle would result in a five percent fuel consumption increase on CNG compared to gasoline. Similarly, the transit bus would have a seven percent increase in fuel consumption.

Combining the relative engine efficiencies, the fuel storage weight impacts and the fuel prices previously presented yields the relative total vehicle fuel costs shown in Table 4-8. For the reasons given in Chapter 3, the gasoline comparison is based upon the stoichiometric combustion CNG engine performance while the diesel fuel comparison is based upon the lean-burn combustion CNG engine. As can be seen from the table, the stoichiometric combustion CNG engine offers significant potential fuel cost savings over an equivalent gasoline vehicle. Conversely, the fuel economics of replacing a diesel engine with a dedicated CNG engine are not as good, especially with current CNG technology. This was to be expected given the fact that diesel engines already represent a very efficient form of fuel combustion and the relatively low cost of diesel fuel compared to gasoline.

Table 4-8

Vehicle Fuel Costs (Gallon Equivalent)

Gasoline Comparison*

	Current	Optimized
Gasoline	$1.08	--
CNG - Stoichiometric Combustion	$0.67-1.12	$0.63-1.07

Diesel Comparison**

	Current	Optimized
Diesel Fuel	$0.95	--
CNG-Lean Burn Combustion	$1.18-2.01	$1.06-1.81

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* Cost per gallon, or equivalent gallon, of gasoline.

** Cost per gallon, or equivalent gallon, of diesel fuel.

V. Heavy-Duty CNG Engine and Vehicle Costs

A. Engine Costs

There is currently very little information available on the cost differential between a heavy-duty CNG engine and a heavy-duty gasoline or diesel-fueled engine. What information is available characterizes the costs associated with converting a diesel-fueled engine to either dual-fuel or dedicated spark ignition CNG operation. Estimates show that conversions of diesel engines to dedicated spark ignition CNG operation range in cost from $3,100 to $5,600. [11] These cost estimates are for engine conversion only and do not include such vehicle-related components as CNG fuel cylinders.

Although conversion has historically been the method for obtaining heavy-duty CNG engines, there is a clear movement within the heavy-duty industry toward the introduction of dedicated CNG engines by original equipment manufacturers (OEM). This is evidenced by Cummins' commitment to offer its CNG L-10 engine starting in 1991. Also, most major heavy-duty diesel manufacturers are currently involved to some degree in the development and assessment of dedicated CNG engines.

It is difficult to predict with any accuracy what the cost of an OEM-supplied dedicated CNG engine will be. In general, though, the bulk of the costs associated with conversion to dedicated CNG operation are for new CNG-optimized parts to replace the diesel-optimized parts, such as the pistons, piston rings, cylinder heads, camshaft and intake manifold. For OEM engines these parts would likely be similar in cost to current parts. The addition of a spark ignition system would be needed at some cost. Some savings may be possible with the fuel system depending on the type of system used (i.e., mixer, port injection, direct injection, prechamber) since the diesel fuel injection system which it would replace is generally regarded as one of the more expensive systems on a diesel engine. Some initial recovery of research and development costs is expected to result in a higher engine introduction cost than would be expected in the long run. In general, however, EPA expects that an OEM mass-produced, dedicated CNG heavy-duty engine would have at most only a modest price increase over a comparable diesel or gasoline engine and that this cost would not be large in comparison with the total engine cost.

B. Vehicle Costs

As with CNG engines, there are some vehicle modifications which would require the engineering and developments costs to be recovered in initial vehicle offerings without resulting in a significant long term price increase for the affected components. These would primarily include modifications to the frame and engine compartment to accomodate the CNG fueling system (i.e., storage cylinders, pressure regulators, refueling interface). Also, the exhaust catalysts to be used on CNG vehicles are not expected to differ significantly in cost from those currently used on gasoline vehicles or those expected to be used on diesels. If CNG were replacing a diesel equipped with a trap oxidizer for particulate control, significant cost saving would result. However, the degree of trap oxidizer use to be expected for diesels is unclear and difficult to predict at the present time.

The only area which is expected to increase the cost of heavy-duty CNG vehicles to any significant degree is that of fuel storage. As was discussed in Chapter 3, fiber-wrapped steel tanks are currently the most likely choice for CNG vehicle use. Fiber-wrapped aluminum cylinders also offer some weight advantages at an increased price. The current prices of some typical cylinders are shown in Table 4-9.[19,20] It is apparent from the table that several cylinders would be required to have any reasonable amount of storage onboard. For reference, The Flxible Corporation (transit bus manufacturer) quotes a typical transit bus diesel fuel tank at $1,134.[21] It is readily apparent that the fuel storage cost would increase several times when moving to CNG, as is shown in Table 4-10. However, this is still a modest price increase when one considers the base price of a diesel-powered Flxible bus ($173,120). This cost, however, would be more difficult to absorb in a much smaller vehicle. It is also apparent that in some applications the available space may make adding sufficient fuel storage capacity for equivalent range difficult or impractical.

Table 4-9

Prices of Typical CNG Storage Cylinders

Type	Size (inches)	Capacity (SCF)	Equivalent Capacity (gal) Gasoline	Equivalent Capacity (gal) Diesel Fuel	Purchase Volume	Unit Cost
Fiber-wrapped Steel	14 x 43.6	750	6	5.5	1-49	$ 610
					200+	470
	14 x 53.6	950	7.5	6.9	1-49	$ 727
					200+	561
	16.3 x 31.6	720	5.7	5.3	1-49	$ 644
					200+	497
	16.3 x 53.6	1260	10	9.2	1-49	$1007
					200+	777
Fiber-wrapped Aluminum	13 x 57.4	825	6.6	6	50-100	$2,400*

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* Current price for low volume - may eventually fall below $1500 with dedicated production equipment and large quantities.

Sources: References 19 and 20.

Table 4-10

CNG Fuel Storage Costs

	UPS Vehicle	Urban Bus
Number of CNG cylinders (16.3x53.6in)	3	11
CNG cylinder cost*	$2,330-3,000	$8,500-11,000
Fuel tank savings	$340	$1,134
Net fuel storage cost**	$1,990-2,660	$7,366-9,866

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* Price range is result of purchase volume range.

** This is a worst case approach, as CNG vehicles may not require equivalent energy storage capacity as conventional vehicles (for example: the BUG bus uses less than one-third of the equivalent diesel capacity a day).

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CHAPTER 5

AIR QUALITY IMPACTS OF CNG USE IN HEAVY-DUTY VEHICLES

I. Introduction

Compressed natural gas (CNG) is an alternative fuel that has the potential to provide significant benefits for urban air quality. This chapter will provide an analysis of the overall air quality impact of using CNG as a fuel for heavy-duty vehicles, focusing especially on its impacts on urban ozone levels, air toxics, and global warming. Emissions of both CO and NOx will also be briefly touched upon.

As was noted earlier, CNG technology is still undergoing development and optimization. As such, it would be inappropriate to discuss the impacts of CNG vehicles based only on current emission levels. Thus, this analysis will compare both current and advanced CNG vehicles to the corresponding petroleum-fueled vehicles. Also, the analysis is structured to allow comparison of lean-burn CNG technology to comparable diesels, and stoichiometric CNG emissions to gasoline-fueled engines. This is appropriate because the lean-burn engine was derived from a diesel engine and will likely replace diesel engines, while the stoichiometric engine was derived from and will likely be used primarily as a replacement for, gasoline-fueled engines. As was noted in Chapter 3, there are currently different test cycles for diesel and gasoline-fueled (or Otto-cycle) engines. To allow for proper comparison to gasoline-fueled vehicles, the stoichiometric CNG emissions listed here are from the Otto-cycle testing.

II. Urban Ozone Levels

One of the most notable air quality benefits of CNG use is its ability to reduce the contribution of mobile sources to the urban ozone problem. This benefit could be significant with respect to heavy-duty vehicles, since traditional heavy-duty vehicles account for about one-fifth of mobile source ozone precursor emissions. The effect of mobile source control programs on urban ozone levels is generally estimated from the change in non-methane hydrocarbon (NMHC) emissions alone, even though a given change in emissins does not produce a linear change in ozone levels because urban ozone formation is a complex process involving the chemical reactions of NMHC and NOx. (The effect of CNG use on NOx emissions is discussed further below.) Futhermore, when comparing completely different fuel-types (such as CNG and petroleum) the issue of photochemical reactivity can become equally important. Most NMHC emissions from CNG vehicles are very light paraffins such as ethane or propane.[1] These species are generally less reactive than the NMHC emissions from petroleum-fueled vehicles.[2,3] Thus, the benefit from NMHC reductions achieved by using CNG would be expected to be enhanced by a reduction in the reactivity of the emissions as well. On the other hand, however, CNG vehicles also emit such highly reactive compounds as formaldehyde and propylene.[1] These emissions may offset this benefit to some extent. Unfortunately, due both to the complexity of the photochemistry of urban ozone formation, and the fact that only a limited amount of speciated exhaust hydrocarbon data for CNG vehicles is available, it is not possible to quantify this additional effect at this time. Thus in this analysis, only the relative NMHC emissions are shown, but the reader is reminded that the actual ozone benefit may be be greater than that estimated simply from NMHC reductions. This is different from how the Agency has been handling the impacts of methanol-fueled vehicles; which emit primarily only two components (methanol and formaldehyde). The photochemistry of both of these compounds is, however, fairly well understood, partly because they are both one carbon molecules that have simpler chemistry than larger molecules. It is clear, though, that further information on the speciation of NMHC emissions from heavy-duty CNG vehicles is needed before their relative impacts can be fully quantified.

The estimates of emissions from petroleum-fueled vehicles which will be used here correspond to engines in a condition similar to the CNG engines that were used as the basis for estimates of the emissions from CNG vehicles (i.e., well-maintained low-mileage test engines). As was noted in Chapter 3, this condition was used as the basis for emissions estimates because it is the only condition for which sufficient data are available for CNG vehicles. Some CNG engines have shown a tendency toward high in-use emissions, but EPA expects these difficulties to be dealt with as the technology matures. Thus, it must be emphasized that the actual in-use effects of CNG vehicles relative to petroleum-fueled vehicles could be different from those described here, either better or worse, depending on in-use emission variability and deterioration.

The estimates of exhaust emissions from 1991 diesels have been selected to represent expected emissions of 1991 bus engines. They were calculated using manufacturers' test data, and scaling the emissions to meet newer standards for NOx and particulate. Bus engines were used for the current estimates since urban buses represent a prime application for lean-burn CNG engines in the near term. Farther into the future CNG engines could be used more broadly in other diesel applications, since all diesels will need to meet the stringent particulate standards after 1994. The 1994 diesel estimates are the results from testing of a prototype of a advanced-technology 1994 diesel (non-bus) engine produced by Navistar.[4] Diesel exhaust emissions are summarized in Table 5-1.

Table 5-1

Petroleum-Fueled Diesel Exhaust Emissions (g/BHP-hr)

Pollutant	Current Bus Engines 1989 6V92	Current Bus Engines 1990 L10	1991 Projected	1994 Navistar[1]
CO	1.5	2.5	1.7[2]	1.4
CO_2	640	549	622[3]	574
NOx	8.2	5.01	4.5[4]	4.44
PM	0.32	0.37	0.22[5]	0.08
NMHC	0.63[6]	0.46[6]	0.40[6]	0.29[6]
Total HC	0.66	0.48	0.42[7]	0.30

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1. Emissions after catalytic treatment.
2. Average of 6V92 and L10 CO emissions weighted by relative sales volumes (80%/20%).
3. Average of 6V92 and L10 CO_2 emissions weighted by relative sales volumes.
4. Needed to meet 1991 standards.
5. Needed to meet 1991 heavy-duty diesel standards. Bus standard is 0.1 g/bhp-hr.
6. 95 percent of total HC for diesel engines (EPA-45012-88-003a).
7. Average of ratios of total HC to PM for 6V92 and L10 engines weighted by relative sales volumes and multiplied by PM level need to reach 1991 standard.

In addition to exhaust, estimates of evaporative emissions, running losses and refueling emission are also needed. To date there is no data suggesting that diesels have significant evaporative or running loss emissions, so these are assumed to be zero. Diesels also have minimal refueling emissions due to the low volatility of diesel fuel. Preliminary EPA data have shown such emissions from diesels to be on the order of 0.05 g/gal, which on a g/BHP-hr basis is somewhat less than 0.01g/BHP-hr.[5]

The estimates of current gasoline exhaust emissions are based on data from manufacturer testing of certification engines. The exhaust HC and CO emission factors (Table 5-2) were calculated by averaging emissions of 1989 heavy-duty gasoline engines which were actually certified to the heavy-duty standards. This means that all engines that did not meet the standards, but were certified by paying non-conformance penalties or through use of the "five-percent option,"* were excluded. This average total hydrocarbon emission factor was multiplied by 0.75 to convert it to NMHC. (Heavy-Duty gasoline-fueled engine emissions are assumed to be about 25 percent methane. There is some uncertainty in this figure, but it represents a reasonable assumption, and using a somewhat different value would not significantly impact the analysis.) The CO_2 emission factor comes from data on the base GM 454 engine from which the CNG engine was derived. NOx levels are those needed to meet the 1991 NOx standard.

Non-exhaust NMHC emissions (see Table 5-4) for current heavy-duty gasoline engines are based on MOBILE4. The evaporative emission factor came directly from MOBILE4, and the running loss emission factor is an average of MOBILE4 estimates of running losses at 87 and 95°F. These temperatures were used because they bracket the temperatures typical of days with high ozone levels in major cities. The refueling emission factor comes from MOBILE4, assuming a brake specific fuel consumption of 0.531 lb/BHP-hr., as was done in Chapter 3.

The emissions from future heavy-duty gasoline-fueled engines also need to be adjusted for the impacts of the President's proposed clean air act amendments. The estimates of gasoline-fueled vehicle emissions under the President's proposal are the current emissions corrected for enhanced

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* This option allows a manufacturer to certify up to five percent of its engines to the non-catalyst standards. The same option would be available to CNG engines. Non-conformance penalties, on the other hand, are not a viable long term strategy for either engine type.

Table 5-2

Gasoline-Fueled Vehicle Exhaust Emissions (g/BHP-hr)

CO	9.2*
CO_2	753**
NOx	4.5***
NMHC	0.45****
Total HC	0.60*

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* Average of 1989 certification results for engines certified to the 14.4 g/BHP-hr CO and 1.1 g/BHP-hr HC standards.

** Certification CO_2 emissions from GM 454 gasoline-fueled engines.

*** Needed to meet 1991 standard.

**** 75 percent of total HC.

evaporative emissions controls, lower gasoline volatility limits, and for the implementation of Stage II refueling controls in non-attainment areas. EPA estimates that the lower volatility limits would result in a 48 percent reduction in evaporative emissions and a 16 percent reduction in running loss emissions. In its analysis supporting its evaporative emissions rulemaking, EPA estimated that, when consideringnon-tampered heavy-duty vehicles, enhanced evaporative controls would result in a 40 percent reduction in evaporative emissions and an 80 percent reduction in running loss emissions when using a 9 psi gasoline.[6] Refueling emissions would be affected by two aspects of the President's program: reduction of fuel volatility to 9 RVP and the implementation of Stage II controls in selected non-attainment areas. The exact amount of control to be realized by the State II requirements is a function of the degree of coverage of the program (station size exemption level) and the degree of enforcement exercised by the states. Based upon the experience of several state programs, EPA has selected a station exemption cutoff of 10,000 gallons per month for these estimates. With this cutoff, Stage II efficiency has previously been estimated to lie between 57 percent and 79 percent.[7] Using the mid-point of this range (68 percent), and recognizing that Stage II controls will not significantly control the spillage portion of refueling emissions, an overall Stage II efficiency of 64 percent results.

The estimated emissions of non-methane hydrocarbons (NMHC) from both optimized and non-optimized CNG vehicles (from Chapter 3), diesel vehicles and gasoline-fueled heavy-duty vehicles are shown in Tables 5-3 and 5-4. Table 5-3 shows that CNG vehicle NMHC emissions are 67-80 percent less than those from the advanced diesel. While this is a significant reduction on a percentage basis, it must be noted that the absolute reductions are small, because diesel emissions themselves are only a few tenths of a gram per brake horsepower hour. It should also be re-emphasized that this comparison does not account for in-use performance differences. The actual reductions will likely be smaller than this since diesels do not rely on exhaust aftertreatment for significant control of NMHC emissions, and thus will probably have less in-use deterioration than CNG vehicles.

The potential reductions are much greater for stoichiometric CNG vehicles relative to gasoline-fueled vehicles. Table 5-4 shows the emissions from the stoichiometric CNG engine are 93-96 percent less than those of gasoline-fueled vehicles. The larger reduction arises because of the fact that, while the advanced lean-burn and stoichiometric CNG engines have similar emissions, the gasoline vehicle NMHC emissions are roughly four times as high as those

Table 5-3

NMHC Emissions From Diesel and Lean-Burn CNG Engines*

	1991 Diesel	1994+ Diesel	Current Lean-Burn CNG	Optimized Lean-Burn CNG
Exhaust (g/BHP-hr)	0.40	0.29	0.09	0.06
Evaporative (g/MI)	0	0	0	0
Running Loss (g/MI)	0	0	0	0
Refueling (g/BHP-hr)	0.01**	0.01**	0	0
Total (g/BHP-hr)	0.41	0.30	0.09	0.06
Corrected for range and performance			0.10	0.06***
Percent Reduction from 1994+ diesels			67%	80%

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* Emission factors are based on testing of well-maintained, low-mileage test engines. In-use emissions would be expected to be higher.

** Unpublished EPA data.

*** The effect of correctio for range and performance was small enough to dissappear in the roundoff to two significant digits.

Table 5-4

NMHC Emissions From Gasoline-Fueled and Stoichiometric CNG Engines*

	Gasoline	Gasoline under President's Proposal	Current Stoich CNG	Optimized Stoich CNG
Exhaust (g/BHP-hr)	0.45	0.45	0.09	0.05
Evaporative** (g/mi)	1.10	0.34	0	0
Running Loss** (g/mi)	2.04	0.34	0	0
Refueling (g/BHP-hr)	0.45	0.18	0	0
Total (g/BHP-hr)	3.70	1.24	0.09	0.05
Corrected for Range and Performance			0.09***	.05***
Percent Reduction from Gasoline under President's Proposal			93%	96%

---

* Emission factors are based on testing of well-maintained, low-mileage test engines. In-use emissions would be expected to be higher.

** Evaporative and running loss emissions are reported as g/mi and converted to g/BHP-hr in the total by the conversion factor .89.

*** The effect of correction for range and performance was small enough to dissappear in the roundoff to two significant digits.

from diesels. As noted above, this means that CNG vehicles would be expected to have a positive impact on urban ozone formation, even without considering the possibility of any reactivity benefit.

It should be noted that these emission factors are all calculated on a g/BHP-hr basis. Actual on-road emissions of CNG vehicles relative to current vehicles would be slightly higher due to an increase in fuel tank weight needed to provide equivalent range and performance. It has been estimated that to achieve equivalent range CNG vehicles would require 26.8 additional pounds (using wrapped steel tanks) for each gallon of equivalent petroleum-fueled vehicle tank capacity.[8] A previous EPA analysis has shown that this weight increase would be compounded by a factor of approximately 1.3 to account for other necessary modifications to the vehicle to carry the additional weight.[9] For a 16,000 pound gasoline-fueled vehicle with a 30 gallon fuel capacity, and a 37,000 diesel bus with a 100 gallon fuel capacity, achieving equivalent range with a CNG vehicle would require increasing vehicle weight by 6.5 and 9.4 percent respectively. For this analysis it was also assumed that to achieve equivalent performance, the horsepower would need to be increased by the same percentages. EPA has previously derived sensitivity factors for the percent change in fuel economy from changes in vehicle weight and horsepower.[9] It was estimated that for light duty vehicles, fuel economy decreased by 0.329 percent and 0.454 percent for each percent change in weight and horsepower respectively. In the absence of factors for heavy-duty vehicles, it is assumed that these factors can be applied to heavy-duty vehicles as well. Thus, the range and performance adjustment factors used in this analysis are 1.05 for the stoichiometric engine emissions and 1.07 for the lean-burn engine emissions. The relative NMHC emissions of CNG vehicles are calculated by multiplying the ratio of g/BHP-hr emission factors by 1.05 or 1.07. These relative NMHC emissions are summarized in Figure 5-1.

III. Air Toxics

CNG is expected to provide significant benefits with respect to air toxics. EPA has presented its estimate of the impact of conventional mobile sources on air toxic in great detail previously.[10] The analysis in this chapter uses the estimates from that work of cancer incidences caused by heavy-duty vehicle emissions to provide a perspective on the toxics impacts due to heavy-duty vehicles. It then develops an estimate of the per-vehicle reductions expected to result from CNG use.

FIGURE 5-1A
RELATIVE DIESEL/CNG NMHC EMISSIONS
Heavy-Duty Vehicles

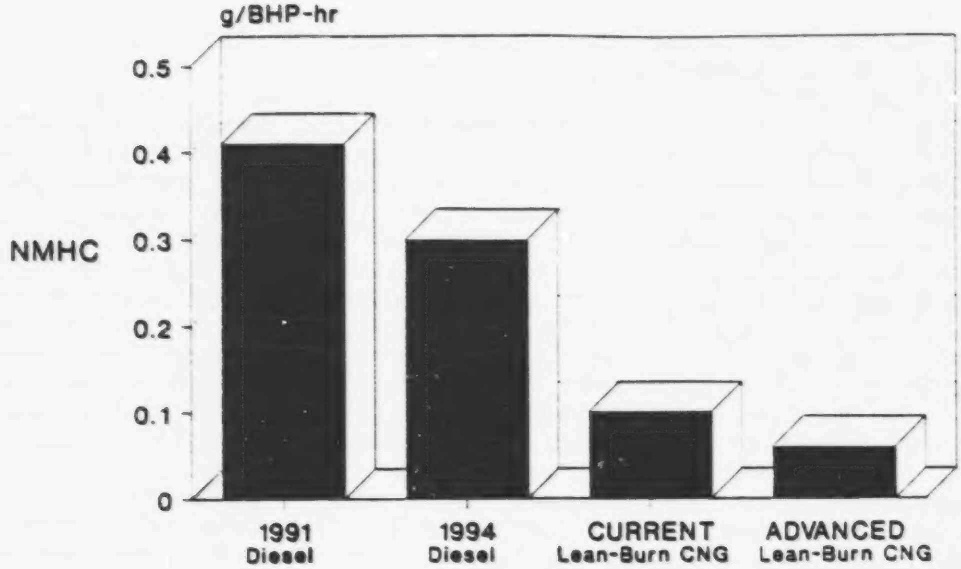
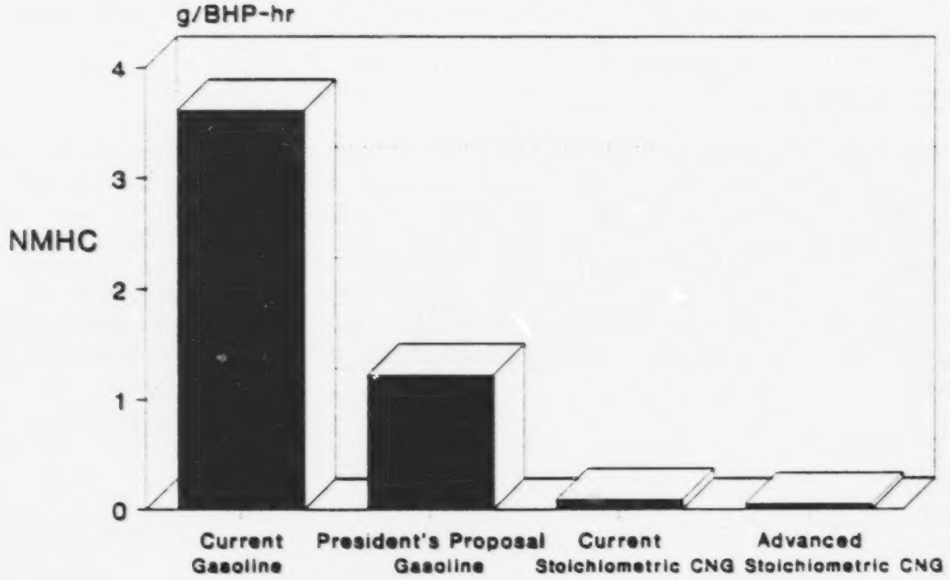


FIGURE 5-1B
RELATIVE GASOLINE/CNG NMHC EMISSIONS
Heavy-Duty Vehicles



The following mobile source-related toxic pollutants were examined: benzene (including exhaust, evaporative, running loss, and refueling benzene), gasoline refueling vapors, exhaust 1,3-butadiene, polycyclic organic material (POM) absorbed onto gasoline-derived particulate matter, and formaldehyde. These pollutants are emitted by diesel and/or gasoline-fueled vehicles and are classified by EPA as either known or probable human carcinogens. The base heavy-duty vehicle cancer cases in the year 2005 from petroleum fueled vehicles are shown in Table 5-5. Included are cases predicted for the nine cities affected by the light-duty alternative fuels program included as part of the President's clean air program.[11] These nine cities are expected to be those most likely to use alternative fuels to combat their severe ozone problems. This choice was also made to be consistent with the other EPA reports on alternative fuels. Since these projections are directly proportional to population, they could easily be extrapolated to larger areas.

Formaldehyde in ambient air includes both "direct" and "indirect" formaldehyde. Direct formaldehyde is emitted in the exhaust of vehicles, while indirect formaldehyde is formed in the atmosphere from the reactions of various reactive hydrocarbons. As discussed in the Final Rulemaking for methanol-fueled vehicles, indirect formaldehyde is responsible for the majority of the formaldehyde in ambient air.[12] However, this is not true when dealing with that portion from heavy-duty vehicles, since they emit a higher fraction of formaldehyde directly.

The estimate of the impact of diesel particulate emissions was done under the assumption that all diesels will need trap oxidizers to meet the stringent post-1994 particulate standards, and includes the impacts of traps failing in use. More recent developments, however, suggest that trap use may not be so pervasive; other, more reliable technologies may be used. Thus the actual total risk from diesel particulate emissions is expected to be somewhat lower than this estimate. In addition, since in-use deterioration is a factor in all of the risk estimates in Table 5-5, the per-vehicle reductions developed below cannot properly be applied to these numbers. Comparisons of the two sets of numbers can, however, be used to provide a perspective on the potential benefits available.

As can be seen from Table 5-5, heavy-duty vehicles are predicted to contribute to about 35 annual cancer incidences in these nine major cities. This is approximately one-half the number estimated for light-duty vehicles (69),[13] and when diesel particulate effects are excluded the heavy-duty contribution drops to about one-sixth (which is expected, given the fact that heavy-duty vehicles account for only one-fifth of mobile source VOC emissions in general). Nevertheless, on a per-vehicle basis the impact of CNG use on air toxics can be significant.

Table 5-5

Air Toxics From Traditional Mobile Sources

Toxic	2005 Base Heavy-Duty Cancer Cases In Nine Cities	Cases Due to Diesel Emissions	Cases Due to Gasoline Emissions
Exhaust Benzene	1.47	0.53	0.94
Evaporative Benzene	0.20	0.00	0.20
Running Loss Benzene	0.05	0.00	0.05
Refueling Benzene	0.06	0.00	0.06
Gasoline Refueling Vapors (W/O Benzene)	0.35	0.00	0.35
Exhaust 1,3-Butadiene	4.29	2.74	1.55
Exhaust Gasoline POM	3.09	0.00	3.09
Direct Formaldehyde	0.08	0.55	0.33
Indirect Formaldehyde	0.66	0.42	0.24
Diesel Particulate	24.10	24.10	0.00
Total	35.15	28.34	6.80

The per-vehicle air toxic reductions for CNG vehicles were calculated by comparing the toxic emissions of CNG vehicles to those of petroleum-fueled vehicles. This was straightforward for the evaporative, refueling, and running loss emissions, since CNG vehicles would not normally have such emissions. The exhaust benzene emissions for CNG were based on very limited speciated hydrocarbon data found in reference 1, where the emissions of benzene were estimated to be one percent of the NMHC emissions. (Benzene emissions from gasoline and diesel engines were estimated to be 3.5 percent and 1.1 percent of HC emissions respectively.)[10] The presence of benzene in CNG exhaust is somewhat surprising, since CNG itself does not contain any benzene, and it would not be expected to form during combustion. The only remaining source of benzene would be the lubricating oil. Clearly, more data are needed in this area. The reduction of 1,3-butadiene emissions is very difficult to estimate for CNG vehicles, since it is difficult to distinguish 1,3-butadiene from butane when speciating hydrocarbons. It seems unlikely that CNG vehicles would have large emissions of 1,3-butadiene, but they may have some. Therefore, for this analysis, it was assumed, that CNG vehicles would result in a near total (99 percent) reduction in 1,3-butadiene. The direct formaldehyde impact was estimated from the emission factors listed in Chapter 3, and by assuming (as was done in reference 10) that formaldehyde accounts for 3.1 percent of gasoline HC emissions and 3.0 percent of diesel HC emissions. The indirect formaldehyde impact was assumed proportional to NMHC reductions, and the diesel particulate reductions were based on the particulate emissions factors listed earlier.

Table 5-6 shows the relative reductions in toxic emissions from CNG vehicles compared to future petroleum-fueled vehicles, for both current technology and for future optimized technology. (These estimates were adjusted for range and performance in the same fashion as the NMHC emissions.) In most cases, the CNG vehicles show major reductions in air toxics. In fact, the only toxics in which the reductions are below 70 percent are the direct formaldehyde and diesel particulate impacts for the diesel/lean-burn comparison. The direct formaldehyde emissions may very well be lowered significantly in the future by technological advances such as catalysts specifically designed to control formaldehyde. The reduction in diesel particulate is below 70 percent because the advanced 1994 diesel engine already has very low particulate emissions so as to meet the stringent particulate standards that take effect in 1994. When all the emissions are considered, the lean-burn CNG engines are expected to result in approximately a 19-35 percent reduction in per-vehicle toxic emissions compared to diesel engines. The stoichiometric CNG engine would be expected to result in approximately a 99

Table 5-6a

Per-Vehicle Air Toxic Reductions of CNG Vehicles Compared to Diesels

Toxic	Percent Reduction Current Lean-Burn	Percent Reduction Optimized Lean-Burn
Exhaust Benzene	71	81
Evaporative Benzene	NA	NA
Running Loss Benzene	NA	NA
Refueling Benzene	NA	NA
Gasoline Refueling Vapors (W/O Benzene)	NA	NA
Exhaust 1,3-Butadiene	99	99
Exhaust Gasoline POM	NA	NA
Direct Formaldehyde	(-494)*	(-257)*
Indirect Formaldehyde	68	79
Diesel Particulate	20	33
Weighted Total**	19	35

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* Direct formaldehyde risk would increase.

** Weighted according to Table 5-5 impacts.

Table 5-6b

Per-Vehicle Air Toxic Reductions of CNG Vehicles Compared to Gasoline

Toxic	Percent Reduction Current Stoichiometric	Percent Reduction Optimized Stoichiometric
Exhaust Benzene	96	98
Evaporative Benzene	100	100
Running Loss Benzene	100	100
Refueling Benzene	100	100
Gasoline Refueling Vapors (W/O Benzene)	100	100
Exhaust 1,3-Butadiene	99	99
Exhaust Gasoline POM	100	100
Direct Formaldehyde	99	99
Indirect Formaldehyde	92	96
Diesel Particulate	NA	NA
Weighted Total*	99	99

---

* Weighted according to Table 5-5 impacts.

percent reduction in per-vehicle toxic emissions compared to gasoline engines.* These overall reductions are also shown in Figure 5-2.

One might expect greater overall reductions from CNG vehicles as compared to diesels. However, the comparison here is with future diesels (i.e., 1994) which will have extremely low levels of particulate (see Table 5-1) in order to meet the 1994 diesel particulate standard. Since the diesel toxic impact is largely dominated by particulate, the total percent reduction in air toxics from lean-burn CNG primarily reflects the reduction in particulate.

Of course, the overall impact of these per-vehicle reductions depends on the fraction of the heavy-duty fleet that is eventually replaced by CNG. Since, at this time, it is very difficult to predict overall penetration, this analysis is limited to per vehicle reductions. Also, it should be reemphasized that these predictions are based on low-mileage emissions; thus the actual in-use impacts could be somewhat different. It would be reasonable to assume that since both CNG and gasoline-fueled vehicles use catalysts as the primary means of emission control, the in-use deterioration will be similar. However, this is not true for diesels, which do not rely on exhaust aftertreatment for significant hydrocarbon control, and would be less affected by in-use deterioration than CNG vehicles. On the other hand, diesels are expected to rely on aftertreatment for at least partial control of particulate emissions, while CNG vehicles will not; so in this regard CNG would be expected to have some in-use advantages. Thus, at this time, it is not possible to fully assess the overall in-use impact. It is, however, possible to say that CNG vehicles should offer significant reductions of air toxic emissions from heavy-duty vehicles.

IV. Global Warming

Recently, the greenhouse effect (i.e., the effect of emissions of certain "greenhouse" gases, most notably CO_2, on global temperatures) has been receiving a great deal of attention. Since combustion of different fossil fuels can result in different CO_2 emissions, it is appropriate that the analysis of the environmental impact of CNG vehicles include its CO_2 impact. Because CNG has a higher energy density per carbon atom than traditional petroleum fuels (about 20-30 percent more), there is a potential for reductions in the

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* The composite weightings are based upon the relative contributions from Table 5-5. Based upon the earlier cautions about comparing those values to the per-vehicle reductions, these composite weightings can only be considered to be approximate values.

FIGURE 5-2A
Relative Air Toxics Impacts Diesel/CNG Heavy-Duty Vehicles

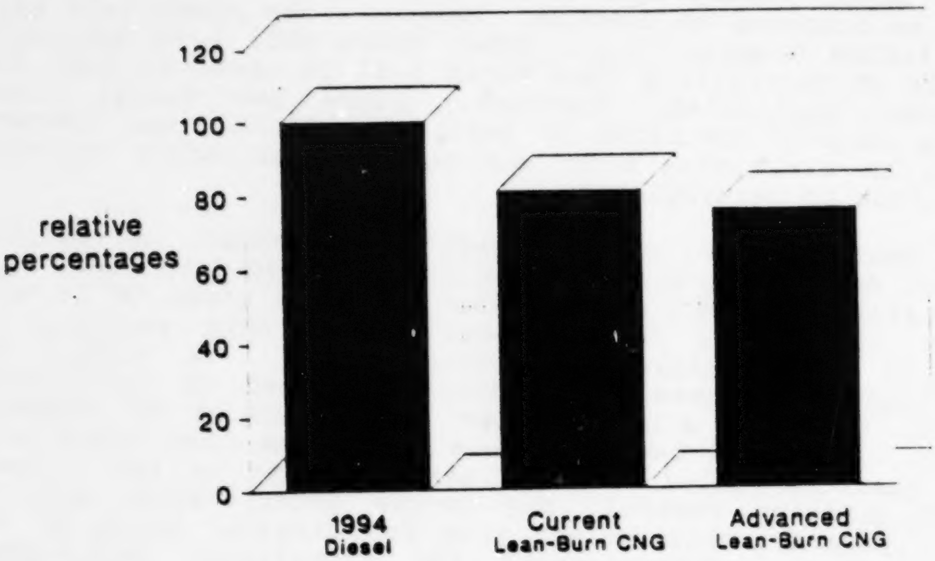
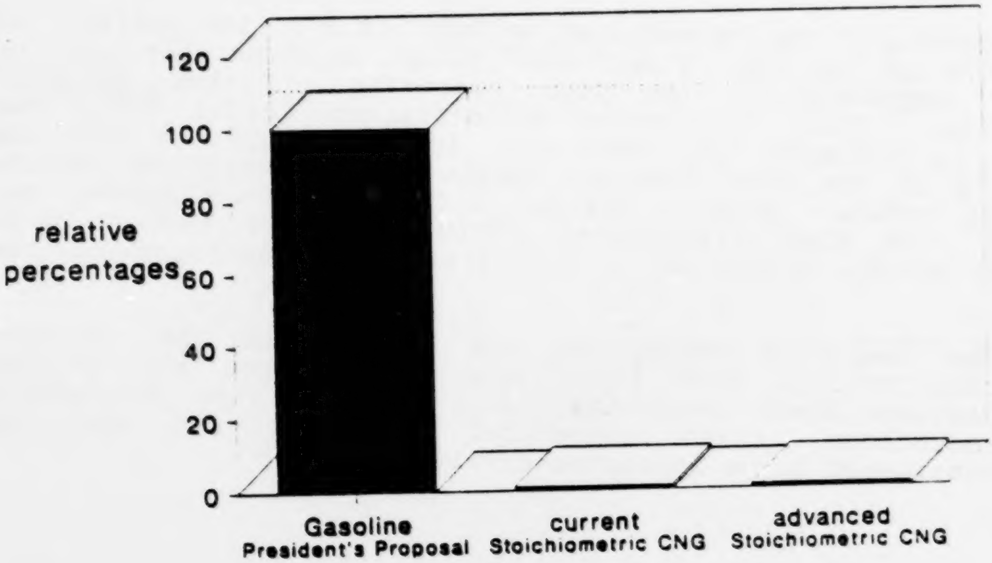


FIGURE 5-2B
Relative Air Toxics Impacts Gasoline/CNG Heavy-Duty Vehicles



global warming impact of motor vehicles. However, this potential benefit can be offset by changes in the energy efficiency of the vehicle.

The estimated CO_2 emissions of CNG vehicles used in this analysis are those described in Chapter 3. The CO_2 emissions of diesels were earlier estimated to be 622 g/GHP-hr for 1991 vehicles, and 574 g/BHP-hr for 1994 vehicles using the same approach used to calculate the NMHC emissions. The emission factor (753 g/BHP-hr) for gasoline-fueled vehicles is from manufacturer test data.[14]

In addition to CO_2, other gases can have a very significant impact on global warming as well. The most important of these, when considering the effect of CNG vehicles, is methane. Methane is much more effective than CO_2 at absorbing infrared radiation; in fact it has been estimated that each molecule of methane in the atmosphere has an effect equivalent to approximately 25 molecules of CO_2 (approximately a 70:1 ratio on a weight basis).[15] Thus any CO_2 emission benefit from CNG vehicles will be offset to some extent by the increased methane emissions, even if the increase in terms of grams per mile is small. Unfortunately though, there is still much debate about other complicating factors. Most significant is the fact that methane is known to have a shorter atmospheric lifetime than CO_2, which would serve to decrease its impact on global temperatures to some extent. There is currently no consensus on what the decrease would be; but it clearly cannot be ignored. This analysis will use a factor from an analysis by the University of California which accounted for both the absorption and atmospheric lifetime effects of methane.[16] EPA is not intending to endorse this study, which made a number of simplifying assumptions in arriving at its results. Rather, it has been chosen as a conservative approach so as not to over emphasize the still uncertain role of methane in global warming. According to the University of California analysis, each gram of methane emitted can be considered equivalent to 11.6 grams of CO_2.

Finally, the total effect of the use of any fuel on global warming also depends on the secondary emissions, both CO_2 and methane, that occur during the production and distribution of the fuel. The energy consumption at all stages of production and distribution can be converted to equivalent CO_2 emissions and added to the vehicular emissions of CO_2 and methane. These effects were analyzed previously in a draft EPA report.[9] There it was calculated that the ratios of secondary CO_2 and methane to vehicular CO_2 emissions for CNG vehicles using domestic gas are 1:3.2 and 1:122 respectively. A similar analysis for gasoline showed the ratios to be 1:4.4 and 1:8720. (The gasoline-based ratios were assumed to be valid for diesels as well.) The fact that the ratios of secondary methane emissions are so different for CNG and gasoline is not surprising since most of the secondary methane emissions for CNG occur during the distribution chain, for which there are no comparable emissions with gasoline.

When considering all of these factors, as is done in Table 5-7, the global warming impact of heavy-duty CNG vehicles appears to be in the same range of that of petroleum-fueled vehicles. Compared to diesels, lean-burn CNG vehicles would be expected to result in a 13-15 percent increase in the global warming impact. However, compared to gasoline-fueled vehicles, stoichiometric CNG vehicles would be expected to achieve a 19-23 percent reduction in the global warming impact. This latter benefit is largely related to the improved efficiency of the CNG engine noted in Chapter 3.

The reader is cautioned that the two sets of figures shown in Tables 5-7a and 5-7b are not directly comparable, as they are derived from different heavy-duty test cycles. As discussed earlier in this report, these test cycles are based on the usage patterns of the engines they represent. The gasoline test cycle (Table 5-7b) is based on the usage patterns of a typical gasoline engine whereas the diesel test cycle (Table 5-7a) is representative of the heavier loads and duty cycles a diesel engine encounters. Earlier discussions (see, for example, Table 3-7) have shown that significantly different emissions result from the change in test cycles.

The results in Table 5-7 show that vehicular CO_2 accounts for about 70-80 percent of the global warming impact, and much of the remainder is due to the energy consumed during the production and distribution of the fuels. Methane emissions play a relatively small role. However, the role of methane estimated here is very sensitive to two assumptions. First, it is obviously dependent on the assumed per gram conversion factor used to convert the methane to equivalent CO_2. Second, it is also dependent on levels of methane control assumed here for CNG vehicles. Both the lean-burn and stoichiometric engines have sufficient catalytic control of methane to be able to meet the heavy-duty engine total hydrocarbon standard. This would not generally be the case, for example, with current light-duty vehicle CNG technology.

It should be noted that this analysis was done assuming that CNG was produced from current domestic production sources of natural gas. The conclusions of this analysis are also sensitive to this assumption. If the CNG was imported from overseas, the CO_2 emitted during production would be doubled, primarily due to the energy consumed during liquifaction and ocean transport of the natural gas. On the other hand, if natural gas that is currently being flared or vented to the atmosphere were used, then clearly the CNG vehicles would provide a very significant

Table 5-7a

Global Warming Impact of Lean-Burn CNG*

Vehicle	CO2	Methane	CO_2 From Production	Methane From Production	Equivalent CO2 **	Range-Adjusted CO2**
Current Diesel	622	0.02	141	0.09	764	764
Advanced Diesel	574	0.01	130	0.07	705	705
Lean-Burn CNG (Current)	575	0.81	180	4.71	819	876
Lean-Burn CNG (Optimized)	525	0.54	164	4.30	745	797

---

* g/BHP-hr.

** Total impact in equivalent CO_2 emissions.

Table 5-7b

Global Warming Impact of Stoichiometric CNG*

Vehicle	CO2	Methane	CO_2 From Production	Methane From Production	Equivalent CO2 **	Range-Adjusted CO2**
Gasoline	753	0.15	171	0.09	927	927
Stoich. CNG (Current)	500	0.63	156	4.10	711	747
Stoich. CNG (Optimized)	480	0.45	150	3.93	681	715

---

* g/BHP-hr.

** Total impact in equivalent CO_2 emissions.

Note: Due to the fact that the lean-burn and stoichiometric analyses are based on different engine test cycles the results shown in Tables 5-7a and 5-7b are not directly comparable and no comparisons should be made between the two.

global warming benefit, since the emissions from the vehicle would be replacing both the vented and flared emissions and the emissions from the petroleum-fueled vehicle simultaneously. Finally, if natural gas were to be produced from coal (as in a large scale CNG program) the CO_2 emitted during production would more than double.

V. Other Air Quality Impacts

Emissions of CO and NOx are also important from an environmental perspective; both can result in adverse health effects. NOx also plays an important role in the formation of ozone in urban areas and can contribute to acid rain. Using the CNG emission projections from Chapter 3 and the petroleum fuel numbers presented at the beginning of this chapter, CO and NOx emissions of the various engine types can be compared. These data are given in Table 5-8.

Turning first to the lean-burn engine, Table 5-8a shows little variation in CO or NOx amongst engine types, except for the current technology lean-burn engine CO value. As described in Chapter 3, EPA expects this value to be reduced significantly in future designs. As for the stoichiometric engine, Table 5-8b shows it to have a significant NOx benefit compared to its gasoline-fueled counterpart. The CNG engine here shows an approximately 90 percent NOx reduction. Low NOx is a characteristic of stoichiometric heavy-duty CNG engines with a three-way catalyst as shown in Table 3-3. Finally, although overall CO emissions are similar, stoichiometric CNG engines may have some CO advantage over gasoline engines during cold start as the gaseous fuel overcomes the need for cold start enrichment.

Table 5-8a

CO and NOx Emissions of Heavy-Duty Diesel/Lean Burn CNG Engines*

	CO (g/BHP-hr)	NOx (g/BHP-hr)
Current Diesel	1.7	4.50
Advanced Diesel	1.4	4.44
Lean-Burn CNG (Current)	4.0	4.50
Lean-Burn CNG (Optimized)	1.5	4.00

---

* Emissions are based on testing of well-maintained, low mileage test engines. In-use emissions would be higher.

Table 5-8b

CO and NOx Emissions of Heavy-Duty Gasoline/Stoichiometric CNG Engines*

	CO (g/BHP-hr)	NOx (g/BHP-hr)
Gasoline	9.2	4.5
Stoichiometric CNG (current)	10.6	0.51
Stoichiometric CNG (Optimized)	7.3	0.41

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* Emissions are based on testing of well-maintained, low mileage test engines. In-use emissions would be higher.

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